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SOME EFFECTS OF LONG-TERM FERTILIZER APPLICATION

ON THE BRETON PLOTS

by

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ABSTRACT

The Breton plots, located in West-Central Alberta,
have been in production since 1930, and since 1938 a con-
tinuous 5 year rotation, consisting of cereals and a forage
mixture has been employed on part of the plots. Treatments
applied to the soil include applications of fertilizer at
low rates, infrequent applications of lime, applications of
manure and some combinations of these. A number of check
plots are included.

Recent observations indicated that alfalfa grew
poorly and comprised a small proportion of the mixed forage
stand on plots receiving NS, NPS and NPKS, compared to plots
receiving lime, lime + NPKS and superphosphate (0-45-0).
These observations prompted a study of the chemistry of the
soil, the composition of the forage and the chemical comp-
osition of alfalfa plants in the mixed forage stand.

Chemical analyses of the Luvisolic (Gray Wooded)
soil of the Breton plots indicate that significant changes
have been induced by the treatments. These analyses indicate
that, compared to check plots, plots receiving NS, NPS and
NPKS are more acidic, and those receiving lime, lime + NPKS
and superphosphate are less acidic. Plots receiving manure
and manure + NPS are similar in acidity to check plots.

The difference in soil acidity between plots is
responsible for the difference in forage composition in the
mixed forage stand. Since 1967 the forage seeded has been
a mixture of alfalfa and brome grass but the forage grown on

the more acidic plots had less than 30% alfalfa in 1971 and 1972. However, on plots receiving lime, lime + NPKS or superphosphate the forage consisted of greater than 70% alfalfa.

Major differences were found in the chemical composition of alfalfa plants in the mixed forage stand. In the most acidic plots alfalfa had, in general, lower N and higher Mn and Al contents than plants grown on plots receiving lime, lime + NPKS and superphosphate. Liming one half of each of the plots resulted in increased N and decreased Al and Mn contents of the plants, especially those grown on the most acidic plots. In a greenhouse experiment alfalfa grew vigorously on soils from the most acidic plots when an adequate supply of NPKS was added to the soil.

The response in alfalfa growth to liming in the field, and to NPKS addition in the greenhouse indicates that lack of available nutrients, especially N, rather than Al or Mn toxicity to the plant is primarily responsible for poor alfalfa growth on the acidic plots. The NS, NPS and NPKS rates applied over a forty year period have been sufficient to increase soil acidity and hence inhibit symbiotic nitrogen fixation but are insufficient to provide an adequate supply of nitrogen for alfalfa growth.

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A. INTRODUCTION

Part of the Breton Plots has been in continuous production since 1930. Since 1938 a five-year rotation consisting of wheat, oats, barley-nursing-hay, first-year hay and second-year hay has been employed on plots 1-11 of series A, B, C, D and F. These eleven plots have, over the past forty-three years received various specific treatments. These treatments include: (a) applications of some commonly used artificial fertilizers; (b) application of manure; (c) application of lime as an amendment; and (d) some combinations of the above. Three check plots are also included.

A brief history of the Breton plots is given by Toogood et al. (1962) and recent changes in fertilizer treatments and ammendments are given in Appendix C.

During the past forty years the composition of the forage seeded has been changed several times. Between 1930 and 1942 sweet clover and altaswede clover were seeded; between 1943 and 1955 a mixture of altaswede clover and alfalfa was seeded; between 1956 and 1966 the mixture seeded consisted of creeping red fescue, timothy, brome, clover and alfalfa and since 1967 alfalfa and brome have been seeded.

In recent years it has been observed that there were striking differences of hay yield, and especially of alfalfa growth between treatments. Furthermore, recent observations have indicated that plots which previously had yielded the most hay were now among the poorest.

In 1971 a study was begun on these plots to invest-
igate the following:

> (a) to study the chemistry of the soil with
> respect to differences between plots which
> may have been caused by long-term fertilizer
> and lime treatment under the five year ro-
> tation;
>
> (b) to study whether these chemical properties
> could explain the differences in growth of
> alfalfa, Medicago sativa, between plots.

B.   LITERATURE REVIEW

1.   Introduction

The purpose of this literature review is to consider earlier research on the influence of fertilizer and lime applications on soil acidity with particular emphasis to their long-term effects.

The more important chemical parameters associated with the infertility of acid soils are discussed, with respect to their influence on the growth and chemical composition of alfalfa, Medicago sativa.

2.   Long-term effects of continuous fertilizer application

(a)   Introduction:

Fertilizer application has been, perhaps, the single greatest contribution to improvement of yield and quality of agricultural products. The "green revolution" which, so dramatically, has been unfolding in the past ten years is providing hope that the imminence of mass starvation can be at least postponed for a short period. This possible delay hopefully can be used to seek solutions to the primary problem of population growth. This "green revolution" will require even more abundant use of artificial fertilizer to achieve maximum production made possible by advances in plant breeding. Both the increase in rate of application and the introduction of fertilizer to soils which had not previously been fertilized will require monitoring of secondary effects. Among these are effects to the soil

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which can occur by applying fertilizers.

There is no doubt that one consequence of applying many of the commonly available sources of nitrogen, sulphur, potassium and phosphorus to the soil is to acidify it. Such secondary effects are not necessarily detrimental to crop production, indeed in alkaline soils they may be decidedly beneficial. The degree of change in soil reaction depends on many variables, especially on the following:

(a) the particular compound,

(b) the rate of application,

(c) the length of period over which it is applied,

(d) the nature of the soil, particularly its buffering capacity,

(e) the crop grown.

All of the above variables can be controlled by proper soil management. The mechanisms by which fertilizer application or amendments alter soil reaction are complex. Some effects of fertilizers on soil acidity are discussed by Adams and Pearson (1967) and Hausenbuiller (1972). Pierre (1928, 1933) developed a concept of "physiological acidic and basic compounds" which is of limited use since it does not take into account the fact that compounds such as KCl, which are neutral in aqueous solution, have an acidic reaction in the soil.

(b) Mechanisms of soil acidification due to fertilizer application:

Acidification may be due to direct effects, chemical or biochemical reactions involving the added compound

or indirect effects, the promotion of selective plant assimilation of soil bases or selective leaching. Pierre (1928, 1933) developed a concept of physiologically acidic and basic compounds and suggested that the potential acidity or basicity could be calculated by subtracting the total equivalents of Ca^{++}, Mg^{++}, K^+ and Na^+ from $SO_4^=$, Cl^-, $H_2PO_4^-$ and $N/2$. Negative answers indicated the potential basicity and positive answers potential acidity of the compound. This concept is of limited use since it does not distinguish between the form of the nitrogen source, whether NH_4^+ or NO_3^- and does not take into account the acidity which can develop when compounds such as KCl, which are neutral in aqueous solution, are added to the soil. The form of nitrogen added however is of fundamental importance. Compounds which contain NH_4^+ or compounds which react in the soil system to produce NH_4^+, for example, urea and anhydrous ammonia, which in aqueous solution are basic, are potentially more acidic than those containing NO_3^-. Ammonium ions in the soil are subject, under favourable conditions, to nitrification. The overall reaction may be represented as follows.

$$NH_4^+ + 2O_2 \longrightarrow H_2O + NO_3^- + 2H^+$$
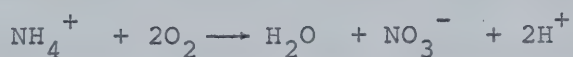
However, the reaction is synergistic involving nitrobacter and nitrosamonas species in particular and the rate of the reaction is rapid under conditions suitable to these micro-organisms. In particular NH_4^+ and NO_3^- concentration, pH, oxygen supply and temperature are important factors which may control the reaction rate (Alexander 1967). Under

conditions favourable to nitrification the net result of
adding NH_4^+ to soil will be an increase in soil acidity due
to the release of H^+ as a product in the reaction. Further-
more NO_3^-, another product, is available to combine with
soil bases such as Ca, Mg and K and together with them may
be leached from the soil. Hausenbuiller (1972) presents
data which indicate the reaction of $(NH_4)_2SO_4$, NH_4NO_3 and
$Ca(NO_3)_2$ incubated in a soil for forty days. The pH of a
slightly alkaline coarse textured soil was unaltered by
$Ca(NO_3)$ but was lowered to approximately 6.2 and 5.4 by
NH_4NO_3 and $(NH_4)_2SO_4$ respectively. An equivalent amount of
nitrogen, 100 ppm, was added in each case. The primary
reason for the difference in reaction of these three com-
pounds is undoubtedly the amount of nitrogen supplied as
NH_4^+ as compared to that supplied as NO_3^-. Under field
conditions however other considerations such as selective
leaching or selective uptake of bases may be important.

Many salts, which in aqueous solutions are neutral
for example KCl, have an acidic reaction in the soil. The
method of estimating potential acidity proposed by Pierre
(1928, 1933) does not account for this acidic reaction.
On addition of KCl to soil K^+ may replace adsorbed Fe^{+++},
Al^{+++} and H^+ from soil colloids resulting in a pH decrease.
Al^{+++} and Fe^{+++} ions so displaced undergo hydrolysis and
produce acidic species (Coleman and Thomas 1967). These
authors indicate that few monomeric aluminum ions exist in
soil above pH 5.5. On addition of $CaCO_3$ to soil Ca^{++} also

displaces adsorbed Al^{+++} and H^+, however in this case HCO_3^- and $CO_3^=$ ions, relatively strong bases, supplied by this compound are available to titrate the acids which result from hydrolysis of displaced cations such as Al^{+++} or Fe^{+++}. The result is a precipitation of Al^{+++} from solution and an increase in calcium saturation on soil colloids. With respect to additions of KCl however the Cl^- ion is an extremely weak base and as such no basic species have been added to titrate the acidic species displaced by K^+ ions. Furthermore Cl^- ions are assimilated by plants to a much lesser degree than K^+ ions and are available to selectively leach bases from the soil.

The mechanisms of soil acidification discussed so far have dealt primarily with the importance of the form of the nitrogen source added, specifically whether NH_4^+ or NO_3^-, and the reactions of some salts which do not undergo microbiological transformations. The importance of the anion both with respect to potential leaching of soil bases, Cl^- and NO_3^-, and with respect to its strength as an acid, $CO_3^=$ and Cl^-, has been discussed. Under field conditions promotion of leaching of bases and promotion of uptake of bases due to increased growth are important. Similarly other aspects need to be considered. In the case of nitrogen compounds these may be partially lost from the soil by denitrification and potential acidity may not develop. Therefore although the potential acidity of a compound may be theoretically estimated the actual acidity which

develops can only be determined empirically under field conditions.

    (c)   Examples of soil acidification due to fertilizer application:

        Voelcker (1874), on analysis of drainage water from Broadbalk field over a four year period, found that ammonium salts applied to the soil greatly increased calcium and magnesium in the leachates. Crowther (1936) presents data of soil analysis of the Woburn plots which demonstrate a striking decrease in both pH and exchangeable calcium as a result of ammonium sulphate application. Plots which had received ammonium sulphate had, in a period of twenty years, become so unproductive that they were subdivided and limed. The data presented by Crowther (1936) indicate that continuous cereal production, over a fifty year period, decreased both soil pH and exchangeable Ca in check plots. However where ammonium sulphate had been added the decrease in both these parameters was much greater than in the check plots. Plots receiving sodium nitrate or manure had less decrease in pH or exchangeable calcium than the check plots, and superphosphate had no effect on soil acidification in the fifty-year period. Collings (1955) indicates that superphosphate has a basic soil reaction. Drastic decreases in pH and consequential yield decline in crop production are also indicated by other authors, particularly those associated with long-term experimental trials (Allison and Cook 1917; Scarsbrook and Cope 1957; Abruna et al. 1958 and Adams et al. 1967). Adams et al. (1967) have shown

that at high rates of applied nitrogen decreases in pH are
detectable deep in the soil profile after a relatively
short period. Similar effects are indicated by Abruna et al.
(1958) and MacLeod et al. (1964). Abruna et al. (1958)
demonstrate that the rate of applied N is important on some
soils. These authors found that the measured acidity
calculated per pound of N added increased with application
rate on two soils but remained constant on a more heavily
textured soil. Adams and Pearson (1967) indicate that
potential acidity need not always develop and cite an ex-
ample where 420 lb/ac N from NH_4NO_3 acidified a soil more
than 840 lb/ac N supplied as urea. Reasons given for this
include more volatilization loss in the case of urea and
also possible leaching and plant assimilation of this com-
pound in molecular form. MacLeod et al. (1964) indicate
that lime applied with the nitrogen fertilizer prevented
development of soil acidity and Hamilton et al. (1966)
indicate that a combination of lime and nitrogen increased
the pH of a Gray Wooded soil more than an equivalent appli-
cation of lime alone.

(d) Present trends in the use of fertilizers with
potentially acidic and basic reaction in soil:

Pierre (1928, 1933) studied the potential
acidification of many fertilizers. He suggested methods of
estimating this potential and proposed means of preventing
it. The potential acidity or basicity of various natural
fertilizer materials is given by Taylor (1953) and Chucka
(1953) and the potential acidity and basicity of some

artificial fertilizer compounds is given by Crittenden (1953).

The preventive solution proposed by Pierre (1928, 1933) was to apply with the fertilizer sufficient bases, usually as calcium carbonate or basic slag. Pesek et al. (1971) indicate that this practice was adhered to in the early twentieth century, but as demand for high-analysis compound fertilizers increased it became uneconomic to manufacture such products. This change in supply put the onus on the user to apply lime as a separate amendment. Pearson (1958) however, indicates that by 1958 the use of lime in the United States had declined while the use of fertilizers continued to rise exponentially. He attributes this decline in the use of lime to decrease in government subsidy. Harre et al. (1971) present the following data which indicate the present preference for high-analysis nitrogen sources.

Table 1$^\emptyset$ Product share of the world N production (%).

Year	$(NH_4)_2SO_4$	NH_4NO_3	Other solid* N sources	Solid Urea	Other[†]
1954	33	25	17	--	25
1968	16	26	3	16	39

* includes calcium nitrate, calcium cyanamid and sodium nitrate (potentially basic sources of nitrogen)

[†] includes anhydrous ammonia; aqua ammonia; nitrogen solutions containing ammonia, urea and ammonium nitrate; ammonium phosphate and other complex fertilizers; and other nitrogen sources.

$^\emptyset$Taken from Harre et al. (1971).

It should be noted that world fertilizer use more than
doubled in this period. In absolute terms therefore the net
total use of potentially basic nitrogen sources has declined.
Other sources have either increased or remained constant.
Several of these have a high potential for soil acidifi-
cation, for example ammonium sulphate and nitrate. Others
such as urea and ammoniacal solutions and gas may have an
initial basic reaction but on reaction in the soil their
net reaction is acidic in the long term.

The consequence of this trend in the increased use
of potentially acidic sources of nitrogen is that soil
acidification will increase, if preventative measures are
not taken, resulting in a decline in agricultural production.

3. Acid soil infertility

(a) Introduction:

Infertility associated with acid soils is generally
regarded as being due to the chemical status of these soils
and their microbial composition and activity. Problems
important in other aspects of soil infertility, such as
structure, are not generally regarded as making a significant
contribution to acid soil infertility.

Changes in soil pH are known to affect the compos-
ition of the microbial populations associated with trans-
formations of nitrogen phosphorus and sulphur (Alexander
1967). Similarly, changes in pH can affect the composition
of the adsorbed cations on clay and organic colloids and
hence the ionic composition of soil solution. The fact

that many major variables change concomitantly makes it impossible to determine, with absolute certainty, the precise factor which is inhibiting growth. Furthermore the difference in tolerance, between plant species and even varieties and cultivars, to soil acidity makes it difficult to assign tolerance levels. Nevertheless most important agricultural crops grow best in soils where pH approaches neutrality and most suffer significant yield decline at pH values lower than 5. This is true of most legumes as these are generally intolerant of low pH.

Alfalfa, Medicago sativa, in particular is sensitive to pH, and its symbiotic bacteria Rhizobia meliloti is even more sensitive, (Robson 1969). Alfalfa also has a relatively high requirement for many nutrients, in particular potassium, calcium and magnesium (Bear and Wallace 1950; Jones 1967); these nutrients tend to decrease in supply as soil acidity increases.

(b) Some major factors in acid soil infertility:

1. Aluminum and manganese toxicity.

Aluminum and manganese toxicity are now generally regarded as being among the major causes of acid soil infertility, particularly in very acid soils. Magistad (1925) and Pierre and Stuart (1933) were among the first to evaluate the significance of aluminum; Funchness (1918) had previously indicated that manganese concentrations as low as 10 ppm were harmful to legumes grown in nutrient solutions. Ouellette and Dessureaux (1958) have demonstrated the effects of both aluminum and manganese on alfalfa composition and

growth. Using sand cultures as a medium, these authors
showed that high levels of calcium could depress manganese
toxicity. Robson and Loneragan (1970) showed that toxicity
of manganese in Medicago species which developed in complete
nutrient solutions containing low manganese concentrations
(o.3 uM), low calcium concentration (250 uM), and neutral
pH could be avoided by either increasing the calcium con-
centration to 2,500 uM or decreasing the pH to 5.4. The
effect of increasing calcium concentration was to decrease
manganese sorbtion, while that of decreasing pH was to
decrease sorbtion and transport of manganese from the root
to shoots. In contrast two cultivars of Trifolium subterran-
eum developed no manganese toxicity symptoms.

Aluminum has been shown to impair phosphorus trans-
location from root to shoot by Pierre and Stuart (1933) and
Foy and Brown (1963, 1964). Ouellette and Dessureaux (1958)
however, found phosphorus content of alfalfa tops to be un-
affected by aluminum levels which seriously restricted
growth. Hoyt and Nyborg (1971a, 1971b) investigated soluble
and exchangeable aluminum and manganese in forty soils in
the Peace River area of Alberta and British Columbia. They
found that yields of barley, turnip-rape and alfalfa were
closely correlated with soil aluminum and manganese. Alfalfa
and rape yield response were closely correlated with soil pH
and percent base saturation, and aluminum and manganese
levels in plants were closely correlated with aluminum and
manganese in the soil.

2. Hydrogen ion toxicity.

Measurement of pH is the simplest and most frequently used method to characterize an acid soil. Toxicity of hydrogen ions, however, is not regarded as being a major problem in acid soils. Coleman and Thomas (1967) emphasize that at pH values normally found in soil, exchangeable hydrogen is not found in large amounts. They attribute the hydrogen ion in solution to be due mainly to the hydrolysis of aluminum.

Lund (1970) investigated soybean tap root elongation in solutions of varying pH and calcium concentration. When pH was maintained at 5.6 no difference in root elongation range was found at different calcium concentrations. However, at pH 4.5 hydrogen ion toxicity caused root growth stunting even at calcium concentrations of 2.5 ppm. Both lateral and primary root elongation were affected. Sutton and Hallsworth (1958), using frequently replenished nutrient solutions, also found calcium to be ineffective in overcoming hydrogen ion toxicity to alfalfa. However, where large-grain sand-solution cultures were used as a growth medium it was found that calcium could readily overcome toxic hydrogen ion effects.

3. Calcium deficiency.

Although calcium is the predominant cation in soil solution in most acid soils (Fried and Shapiro 1961; Adams and Lund 1966) lack of sufficient calcium in plant tissue has been reported (Wallace and Hewitt 1948; Melsted 1953; Foy 1964; Adams and Lund 1966; Evans and Kamprath 1970).

In general, however, calcium deficiency has been dismissed as a major cause of acid soil infertility. Even where calcium deficiency is evident the lack of uptake in plants is attributed to other causes especially calcium-aluminum interactions rather than to low levels of calcium in the soil, (Foy et al. 1969; Long and Foy 1970). Loneragan and Dowling (1958) have demonstrated an interaction between calcium and hydrogen ion concentration on nodule formation in Trifolium subteranneum. At low pH (4.0) no nodulation occurred no matter how high the calcium concentration. At low calcium concentration (0.01 mM) no nodules formed at any pH used. Above these limits nodulation could be promoted by increasing either pH or calcium concentrations.

4. Magnesium deficiency.

Magnesium, like calcium, is decreased by acidification processes and like calcium is not generally regarded as a major determinant of acid soil infertility. Magnesium deficiency has, however, been reported by some authors (Adams and Pearson 1967; Weeks and Lathwell 1967; Woodruff 1967). Adams and Pearson (1967) suggest that in many acid soils there may be a slow release of magnesium from vermiculite and montmorillonite since these clay minerals are more unstable in acidic conditions.

5. Deficiency of other elements.

Molybdenum, as Davies (1956) points out, is more available at high pH than at low pH. Molybdenum deficiency has been shown to be a problem in legume nodulation by

Anderson (1956) and Reisenauer (1956). Both these authors
showed that when an external nitrogen source was added the
requirement of the legume for molybdenum was less than that
of the Rhizobia. Anderson (1956) showed that other defic-
iencies such as sulphur, phosphorus and boron had to be
overcome before molybdenum response was noted.

     Many micronutrient cations are more available to
plants as soil pH decreases. These include zinc, manganese,
iron and copper which in acid soils are more likely to cause
toxicity rather than deficiency problems. The availability
of these micronutrient cations are closely related to
organic matter transformation in soil (Alexander 1967).
This author also indicates that microorganisms may alter
the solubility and oxidation states of these cations and
may similarly affect the micronutrient anion molybdate.

     6. Nitrogen transformations.

          Nitrogen is probably required by plants in
greater quantities than any other nutrient. The bulk of
the nitrogen in soils is, however, in organic combination,
both living and dead, and as such is unavailable to plants.
Nitrogen is assimilated by plants, almost entirely, as
nitrate and ammonium ions. Factors which affect mineral-
ization, the release of ammonium from organic matter, or
nitrification, the conversion of ammonium to nitrate, are
therefore of fundamental importance to soil fertility. The
diverse microflora responsible for mineralization in general
tend to favour neutral or near neutral soil pH   (Alexander

1967). Because of the diversity of microorganisms involved, however, mineralization does not cease entirely, below a given pH.

Nitrification is largely controlled by <u>Nitrosamonas</u> and <u>Nitrobacter</u> and the process is slow under acid conditions. Alexander (1967) emphasizes that while there is no exact limiting pH, the rate of nitrification typically declines rapidly below pH 6.0. Morril and Dawson (1967) observed that the degree of acidity of a soil was the best single indicator of nitrification ability. Other factors, such as oxygen supply, substrate and product levels and temperature could be of critical importance. These authors found maximum nitrification rates occurred, for a wide variety of soils, in the pH range of 5.0 to 6.4 and that rate of nitrification was closely correlated with both soil pH and calcium.

Gerretsen and DeHoop (1957) demonstrated that nitrogen losses during microbial oxidation of ammonium to nitrate were greatest under acid conditions. Losses of both NO and N_2 were as high as 74% of applied ammonium in an acid sandy soil. Paden and Garman (1946) have shown that in general nitrogen is more efficiently used in soil with pH range 5.0 to 7.4 than in those with more acidic or basic pH.

7. Symbiotic fixation of nitrogen.

Loneragan (1960), Vincent (1964) and Robson (1969) have reviewed nitrogen fixation and factors which affect it. Robson (1969) considered the distribution of <u>Rhizobia</u> and the host plant separately. Nutman (1965) has

indicated that nodule bacteria are facultative symbioants
which are able to exist as normal components of the soil
microflora in the temporary absence of their hosts, and
Loneragan and Dowling (1958) have shown that soil conditions
favourable for growth of a nodulated plant may not be
favourable for Rhizobia growth. Robson (1969) found growth
of Medicago species occurred infrequently on moderately
acid sandy soils low in phosphorus. He attributed the low
frequency of Medicago species to the low tolerance of
Rhizobia meliloti compared to other Rhizobia and secondly
to greater intolerance of Medicago species than other legumes
to toxicities associated with acid soils.

Munns (1965a, 1965b, 1965c) has studied the effect
of several chemical parameters on legume nodulation and
growth. He suggests that in moderately acid soils growth
limitation may be due to restriction of Rhizobia and hence
nodulation, but in strongly acid soils nodulation and alum-
inum toxicity were both involved.

Molybdenum deficiency also has been shown to be a
problem in nodulation (Anderson 1956; Reisenauer 1956).
However, the former author suggests other deficiencies such
as sulphur, phosphorus and boron may have to be overcome
before molybdenum response is noted.

4. Effects of Liming

(a) Introduction:

The effect of applying lime as a soil ammendment
or as a means of preventing soil acidity has been known

for more than two thousand years. Recorded data of the benefits associated with this ammendment date back to the previous century (Crowther 1936), but even after one hundred years of extensive research there is still considerable uncertainty as to the specific reactions involved (Coleman and Thomas 1967). Nevertheless the application of lime, both calcitic and dolomitic, is by far the most common and economic method of raising soil pH and avoiding the general malaise known as acid soil infertility.

Application of lime will increase the relative proportion of calcium and/or magnesium occupying the exchange complex by displacement of other cations. Dissociated carbonate ions, being a relatively strong base, can titrate acids in the soil solution. Furthermore, carbonate and bicarbonate anions may form insoluble compounds with some cations resulting in precipitation, other more soluble compounds may be leached downward in the soil profile. The reactions involved are complex and not well understood; for example, our knowledge of the solubility of compounds in pure solution has probably little relation to their solubility in the soil system. Furthermore it is doubtful that an equilibrium is ever reached; lime is generally applied at rates of several tons per acre in an attempt to maintain soil neutrality for many years. Similarly, it is well known that the fineness of the applied lime has a marked influence on reaction rate.

(b) Yield response:

Excellent reviews of the yield response promoted by liming acid soils are given by Adams and Pearson (1967), Jackson et al. (1967), Weeks and Lathwell (1967) and Woodruff (1967). Hamilton et al. (1966) found that modest applications of calcitic limestone still increased yields after seven years on a Gray Wooded soil. MacLeod et al. (1964) indicate significant increases in forage production, and increase in legumes as a percent of total forage production, on liming an acid soil. Scarsbrook and Cope (1957) and Paden and Garman (1946) indicate the benefit of applying both nitrogen and lime and the consequences of nitrogen application alone. Although conversion of ammonium to nitrate is more rapid under neutral than acid conditions and hence is more susceptible in the latter form to leaching loss, Paden and Garman (1946) show that applied nitrogen is more efficiently used as the pH of the soil is increased to neutrality. Pearson (1958) suggests that the more efficient use of applied nitrogen under neutral conditions is due to more rapid plant growth and hence greater uptake of the applied nitrogen. Gerretsen and DeHoop (1957), indicate that losses during nitrification are much greater under acidic conditions.

Hamilton et al. (1966) suggest that lime application on a Gray Wooded soil may have increased the availability of soil phosphorus and Truog (1953) demonstrated that both native and applied phosphorus were more readily available to plants when applied with lime. However, several authors (Lawton and Davis 1956; Neller 1953) have indicated that

lime application can reduce phosphorus availability.
Pearson (1958) suggests that such reduction in phosphorus
availability on limed soils is due to decreased solubility
and points out that in the long term the phosphorus com-
pounds would become available.

Liming has been shown to reduce potassium leaching
from the plough layer of strongly acid soils (Black 1968).
However, liming has also been shown to decrease levels of
exchangeable potassium (Adams and Pearson 1967; MacLeod et
al. 1964) and has been reported to reduce potassium uptake
in broccoli and strawberries (Jackson et al. 1967).
Thomas and Hipp (1968) suggest that liming an acid soil
to pH 6.0 may increase potassium uptake but liming a soil
which already has a pH of 6.0 to 7.5 will generally decrease
potassium uptake.

Response of alfalfa to applied potassium has been
indicated by several workers (Gerwig and Ahlgren 1958;
Twamley 1960; Wang et al. 1953).

Toogood et al. (1962) indicate that the major
response of alfalfa on the Breton plots has been due to
nitrogen, sulphur and phosphorus with little evidence of
response to potassium. These authors indicate that liming
alone was of little benefit. Similarly, Cairns and Carson
(1961) have also found that on some Alberta soils alfalfa
production was greatly enhanced by sulphur application.

5. Recent problems in alfalfa growth in Alberta

In recent years workers in Alberta (Khan 1963;

Webster and DeKock (1970) have indicated problems associated with alfalfa growth which are not readily explicable in terms of nutrient availability. Alfalfa was found to grow poorly on some soils where it had been previously grown. Webster et al. (1967) indicated that small areas of vigorous alfalfa growth were often found throughout a field where the growth in general was poor. In greenhouse experiments conducted with soils from such fields various treatments were found to increase alfalfa growth to a limited extent. These treatments included lime application and nutrient solutions. It was found that nodulation was not increased by these treatments. Sterilization of the soil increased yields substantially on a number of soils and in some cases improved nodulation. In later work (Webster and DeKock 1970), soils and plants grown on them were analyzed for essential nutrients and possible toxicants and it was found that nitrogen was higher in plants grown on soils not previously cropped to alfalfa than on soils where alfalfa had originally grown well but later grew poorly. These authors concluded that the inability of plants grown on these "problem" soils to use nitrogen may be due to a biological toxicant or, in some cases, to aluminum toxicity.

6. Summary of the literature review

Fertilizers, in particular common nitrogen, sulphur, potassium and phosphorus compounds, applied to soil result in acidification. Direct reaction effects of these compounds, selective removal of bases by plants and loss of

bases due to increased mobility by leaching, are all
involved, and will result in infertility associated with
acid soils. In the absence of ameliorative or preventitive
steps many soils, particularly those which are naturally
acidic or weakly buffered, may become sufficiently infertile to
sustain adequate crop growth. Alfalfa, because of its
ability to fix nitrogen, its high yield and protein content,
is an important forage crop in Alberta. However, alfalfa
production is poor on acid soils as both the host plant
Medicago sativa and especially its symbiotic bacteria
Rhizobia meliloti are sensitive to soil acidity. The
latter is very sensitive to Al and Mn toxicity, compared to
the host plant and to many other legumes and their symbiotic
bacteria. Consequently soil acidification should be avoided,
by use of lime, by farmers producing alfalfa on weakly
buffered soils.

MATERIALS AND METHODS

1. Introduction

A diagram of the Breton Plots and a list of the
treatments currently used on plots 1-11 are given in Appendix
C. The site is divided into six series: A, B, C, D, E and
F, which are adjacent strips of land running north to south.
Each of these series is divided into twenty-six plots,
numbered 1-26, all of which receive a specific treatment.
The sequence of treatments is the same in each series such
that Plot 3, for example, is an NPKS treatment on series A
through F. Similarly, plots 1, 5 and 11 are check plots on
all series.

Plots 1-11 of series A, B, C, D and F, the series
which comprise the continuous five-year rotation of wheat,
oats, "barley-nursing-hay", first-year hay and second-year
hay, were sampled for this study.

2. Soils for laboratory analysis

(a) Sampling:

1) Breton Series D (Plots 1-11) -

Core samples, using a mechanical coring device,
were taken from these plots in June, 1971. Four predetermined
locations within each plot were sampled to the C horizon. At
each location the cores were separated into horizons and
stored separately in sealed plastic bags.

2) Breton Series A, B, C, and F (Plots 1-11) -

Core samples were taken from the west half of
these plots in June, 1972. This half alone was sampled

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because the east half of these plots had been limed in the
spring of 1972.

Ten predetermined locations were sampled in each
plot. The entire Ap horizon was removed in each case and
these ten samples were then bulked together in sealed plastic
bags.

(b) Preliminary operations:

All soil samples were spread in a drying chamber,
dried at 35°C for 48 hours and passed through a 5mm sieve.
Residual material including stones and undecomposed plant
material were discarded.

3. Soils for greenhouse experiment

Bulk samples of approximately 70 kg were taken from
the Ap horizons of series D plots 3, 5 and 7 in October,
1971 and from series C, plot 3 in September, 1972. The
samples were spread to air dry and passed through a 0.6 cm
screen to remove stones. After thorough mixing 2 kg samples
were taken, passed through a 5mm sieve and stored for lab-
oratory analyses.

4. Plants for laboratory analysis

(a) Sampling:

1) Breton Series D (Plots 1-11), alfalfa samples -
Samples of alfalfa, Medicago sativa, were taken
from these plots in August, 1971, when this series was in
"first-year hay" of the five-year rotation. Sampling was

conducted just prior to bloom; only the top 15 cm of each plant was taken.

2) Breton, Series F (Plots 1-11), alfalfa samples -

Alfalfa samples were taken from these plots in 1972 when this series was in "first-year hay" of the five-year rotation. Samples were taken from the west half alone as the east half of these plots had been limed in the spring of 1972. Sampling was conducted just prior to bloom; only the top 15 cm of each plant was taken.

3) Breton, Series A (Plots 1-11), alfalfa samples -

Alfalfa samples were taken from these plots in September, 1972, when this series was in "barley-nursing-hay" of the five-year rotation. Separate samples were taken from the east (limed) and west (unlimed) half of each plot. The entire plant cut 2 cm above the ground was taken in all cases as the plants on many of the plots were small.

4) Breton, Series D and F (Plots 1-11), bulk
    forage samples -

Bulk forage samples, of the seeded alfalfa-brome mixture, were taken from these plots. Six predetermined locations, measuring 1 x 0.3 meters, were sampled in each plot. Both series were sampled when they were in "first-year-hay" of the five-year rotation; bulk forage samples being taken on the same day but just prior to the alfalfa samples mentioned in 1) and 2) above.

5) Note on plant sampling -

Because of the relative scarcity of alfalfa plants in many of the plots, it was not always possible to

adhere strictly to a predetermined location-of-sampling plan. Where alfalfa growth was extremely poor, particularly on plots 3 and 4, it was necessary to search throughout the plot in order to obtain sufficient sample for analysis.

(b) Preliminary operations:

All the alfalfa samples were treated in the following manner. On returning from the field they were stored in a cooler at $40^{\circ}C$ and the next day removed and allowed to come to room temperature. They were then immersed in luke warm "deionized water" in order to remove clay and other particulate matter from the surface. The plants were then dried at $60^{\circ}C$ in an oven and ground to pass through a 20 mesh sieve.

The bulk forage samples used for separation analyses were kept frozen; before separation they were allowed to thaw.

5. Laboratory procedures

(a) Soils

Soil reaction pH -

Soil pH in water and in 0.01 M $CaCl_2$, using a soil: solution ratio of 1:2 in each case, was determined as described by Peech (1965), using a glass electrode pH meter.

Exchangeable cations and cation exchange capacity -

Exchangeable cations were extracted from the soil using 1N NH_4OAc adjusted to pH 7.0 as described by the Association of Official Agricultural Chemists (1955). The

concentrations of Ca^{++}, Mg^{++}, Na^+ and K^+ in this extract were determined by atomic absorbtion spectrophotometry. The cation exchange capacity was determined by extraction of adsorbed NH_4^+ with 1N NaCl and distillation of the extract according to the method outlined by the Association of Official Agricultural Chemists (1955).

Nitrogen -

Nitrogen was determined by the Kjeldahl-Wilford-Gunning method (Association of Official Agricultural Chemists, 1955).

Total carbon -

Total carbon was determined by the dry combustion method described by Allison et al. (1965).

Titratable acidity -

Titratable acidity was determined using $BaCl_2$ - Triethanolamine buffered at pH 8.0 as described by Peech (1965).

Extractable Al and Mn -

Extractable Al and Mn were determined using a variety of extracting solutions, 0.01 M, 0.02 M and 0.05 M $CaCl_2$ and 1M KCl. The extraction procedure was as described by Hoyt and Nyborg (1972). However, a one hour shaking period followed by centrifuging at 3,500 r.p.m. for 10 minutes prior to filtration was used. Al and Mn in the filtrate were determined using atomic absorbtion spectrophotometry.

"Field capacity" -

"Field capacity" was determined using a column

method outlined by Miller and McMurdie (1953).

Air-dry moisture content -

Air-dry moisture content was calculated from weight
loss after drying at $105^{o}C$ for 24 hours.

"Available NPKS" -

"Available NPKS" in the soils used in the green-
house experiment were determined by the Alberta Soil and
Feed Testing Laboratory using methods routinely employed to
recommend fertilizer application rates for farmers in Alberta.
"Available N" is based on nitrates alone, "available P" on
$HF-H_2SO_4$ soluble P, "available K" on K extracted by 1N
NH_4OAc (pH 7.0) and "available S" on $SO_4^=$ soluble in 0.01 M
$CaCl_2$.

   (b) Plants:

Nitrogen -

Nitrogen in alfalfa samples was determined by the
Kjeldahl-Wilford-Gunning method (Association of Official
Agricultural Chemists, 1955).

Sulphur -

Sulphur in alfalfa samples was determined by boiling
them in a solution of equal volumes of concentrated HNO_3 and
$HClO_4$, in microkjeldahl flasks for one hour. "Total sulphur"
in this solution was determined by the method described by
Johnson and Nishita (1952).

Cations -

Cations, Ca, Mg, Na, K, Fe, Mn and Al, in alfalfa
plants were determined using a dry-ash procedure outlined

by Isaac and Kerber (1971). Samples were brought to 500°C over a three hour period and then maintained between 500°C and 550°C for a further three hours and allowed to cool overnight. The residue was dissolved in 5 ml of 2M HCl, diluted by adding 5 ml of "deionized" water, heated, quantitatively transferred to a 25 ml volumetric flask and diluted to volume. This solution was filtered through an acid washed filter paper. Ca, Mg, Na, K, Fe, Mn and Al were determined by atomic absorbtion spectrophotometry.

D. RESULTS AND DISCUSSION

1. <u>Soils</u>

(a) Introduction

Apart from any induced differences in the soil on the Breton Plots, due to fertilizer or cropping practice, the soil was variable in its natural state. This variability is illustrated by soil texture, a property which should, in the absence of soil erosion, remain constant over time. Unpublished data on soil texture, made available by Dr. J. A. Toogood and presented in Appendix D, indicate such variability within plots 1-11 and among series D, E and F. These data indicate a range of approximately 10-18% clay and 32-43% sand in series D, E and F plots 1-11. Note that on one plot alone, plot 7, series E, the clay content varies from 13-17% from the east to the west half. This would indicate that soil variability may often be as great over short distances as longer ones, a point emphasized by Cameron <u>et</u> <u>al</u>. (1971).

The variability in soil texture indicated by these data was undoubtedly accompanied by variability in other soil physical and chemical properties. The data presented in Appendix A for the deep core samples on series D indicate considerable variation in depth and occurrence of horizons within and between plots. Such variations in physical and chemical properties make it more difficult to discern differences induced by fertilizer treatments, since they may act either to enhance or mask possible changes.

For example, soils with relatively higher amounts of organic or inorganic colloids are probably more highly buffered than those with lower amounts. Similarly the relative proportion of various cations occupying exchange sites may be very important.

The natural variability in the soil of the Breton plots is illustrated by the following data for $^{Ca}/\Sigma$ and $^{H}/\Sigma$.

Table 2 $^{Ca}/\Sigma*$ and $^{H}/\Sigma\dagger$ for check plots 1, 5 and 11

Series A, B, C, D and F

a) $^{Ca}/\Sigma\%$

			Series		
	A	B	C	D	F
Plot					
1	54.1	53.6	58.0	57.8	62.6
5	55.4	53.2	55.0	64.3	69.9
11	61.2	62.0	64.2	63.7	65.8

b) $^{H}/\Sigma\%$

	A	B	C	D	F
Plot					
1	30.1	30.6	25.6	29.0	23.9
5	30.8	33.2	30.7	24.1	19.3
11	25.3	25.1	22.4	23.2	21.3

$*\Sigma$ = (Ca + Mg + Na + K + H) me/100g

$\dagger_H$ = Titratable acidity

The design of the Breton plots is shown in Appendix C. Note that check plots 1, 5 and 11 occur in the same

position on each series. From the data presented in Table 2 it is evident that values of $^{Ca}/\Sigma$ are higher and values of $^{H}/\Sigma$ are lower in plot 11 than in plot 1 for all the series. Values for these parameters on plot 5 are intermediate between values for plots 1 and 11 in most cases. This indicates an increase in "Ca saturation" and a concomitant decrease in "H saturation" in the south part of the series. On series A, B and C plot 11 is considerably different from plots 1 and 5 which are themselves quite similar with respect to these parameters. In series D and F, however, plots 5 and 11 are quite similar but differ considerably from plot 1 with respect to these parameters.

Even more striking evidence of north-south variation in series D is evident in the average values of exchangeable soil calcium, the dominant cation in these soils, for plots 1 to 11 inclusive. The values for this parameter fall into three subsets (see Table 3). Plots 1-5 inclusive comprise the first subset having a mode of 12.9 me/100g. Plots 6-9 inclusive form the second subset having a mode of 15.4 me/100g. Plot 11 has a value of 17.2 me/100g with plot 10 being intermediate between the second subset and plot 11 with a value of 15.8 me/100g. This indicates that the south part of this series was originally high in calcium. Plot 11 is higher in exchangeable calcium than other check plots and is higher than plots 6, 7 and 8 all of which received applied calcium.

This general trend is not evident in series A and B

but is present in series C and F and reflects the higher
cation exchange capacity in the south portion of the series.
The resultant increased buffering capacity and the higher
absolute value of exchangeable calcium are the most plausible
explanation of why plot 10 (NPS) shows much less acidification
than plot 3 (NPKS) and plot 4 (NS) though all three receive
nitrogen and sulphur at equivalent rates.

In addition to north-south variation, data in Table 2
also indicate an east-west variation with respect to $^{Ca}/\Sigma$ and
$^{H}/\Sigma$. In general going from series A to F (east to west)
there is an increase in $^{Ca}/\Sigma$ and a corresponding decrease in
$^{H}/\Sigma$. North-south and east-west variation is also evident
with respect to soil pH, Mn and Al; see Figures 1, 4 and 5
and Tables 4, 5,6, 7 and 8.

In summary it seems probable that in its original
condition the soil of the area now comprising the plots
was variable. Some evidence exists to suggest higher cation
exchange capacity in the south of the area comprising plots
1-11 and in the western series, particularly D and F. Plots
in these areas tend to have higher "Base saturation" and, in
particular,"Calcium saturation". These trends may be of
major significance in explaining alfalfa growth response
since they may have acted to partially mask differences
indicated by fertilizer treatment. In particular they may
help to explain why plot 10 is less acidic than plots 3 and
4 though all receive nitrogen and sulphur at the same rate.
Furthermore, these trends may also explain why yield of

first-year hay on check plot 11 is generally higher than on
check plots 1 and 5 for all series and why series D and F
have significantly higher yields (see Appendix E) than series
A, B. and C for the majority of plots. Caution, however, is
necessary in comparing yields from different series as they
were cropped to forage in different years and other variables
such as moisture, sunlight hours and frost may have been of
salient importance.

(b) Soil analyses series D (plots 1-11) Ap horizon

The plots on this series were sampled to the C
horizon using four predetermined locations in each plot.
The results of chemical analyses performed are presented in
Appendix A. Averages of the chemical analyses for the Ap
horizon are presented in Table 7. Part of the data from
the four locations in each plot was treated statistically
as a simple randomized experiment having 11 treatments and
four determinations of a given parameter within a treatment.
The following parameters for the Ap horizon were so tested:
pH (H_2O), pH ($CaCl_2$), Ca, Mg, Na, K, H, Ca/Σ, Mg/Σ, K/Σ,
H/Σ. The averages of some parameters found to be signifi-
cantly different between treatments were treated statistically
using Duncan's Multiple Range Test. The results are presented
in Table 3. A number of major trends are apparent in these
results, particularly with respect to pH, ^{H}/Σ and ^{Ca}/Σ par-
ameters which are indicative of soil acidity. It has been
suggested previously that series D may have had an original
trend of increasing cation exchange capacity and exchange-
able calcium from north to south in the plots. The Duncan's

Multiple Range Test for exchangeable calcium on these plots
suggests a persistence of this trend even after fertilizer
and lime application.

It is evident that a number of the treatments differ
significantly from the check plots with respect to pH, $^{Ca}/\Sigma$
and $^{H}/\Sigma$. Plots 3 (NPKS), 4 (NS) and 10 (NPS) all receive
nitrogen and sulphur at the same rate. The pH in plot 3
(NPKS) is significantly lower and $^{H}/\Sigma$ is significantly higher
than check plots 5 and 11. Plot 4 (NS) has a significantly
lower pH (H_2O) than check plots 5 and 11, a significantly
lower $^{Ca}/\Sigma$ than check plot 5 and a significantly higher $^{H}/\Sigma$
than check plots 5 and 11. Plot 10 (NPS) has a significantly
lower pH (H_2O) than check plots 1, 5 and 11, a significantly
lower $^{Ca}/\Sigma$ than check plot 5 and a significantly higher $^{H}/\Sigma$
than check plots 5 and 11.

Considering significantly lower values of pH (H_2O),
pH ($CaCl_2$), $^{Ca}/\Sigma$ and significantly higher values of $^{H}/\Sigma$
to be indicative of soil acidification, a given plot has
a total of twelve possible significant differences from
all three check plots. On this basis plot 3 (NPKS) has
eleven such differences, plot 4 (NS) has five and plot 10
(NPS) has six. Hence it may be argued that plots 3, 4 and
10 are more acidic than check plots, with plot 3 (NPKS)
being more acidic than either 4 (NS) or 10 (NPS). Plot 9
receives manure in addition to NPS and is not more acidic
than the check plots.

If the values of pH, $^{Ca}/\Sigma$ and $^{H}/\Sigma$ for plots 3, 4, 9

and 10 are compared with one another there is generally no significant difference between plots 4, 9 and 10 but plot 3 is in general more acidic than plots 4, 9 and 10.

Plots 6 (L) and 7 (LNPKS) both have significantly higher pH and $^{Ca}/\Sigma$, and lower $^{H}/\Sigma$ than all of the three check plots. It is apparent that the relatively modest and infrequent applications of lime (see Appendix C) are sufficient to cause these changes. The pH of plot 8 (P, 0-45-0) is significantly higher than check plots 1 and 11, $^{H}/\Sigma$ is significantly lower than check plots 1 and 5 but $^{Ca}/\Sigma$ is significantly lower than only check plot 1.

In concluding this discussion of statistically significant differences between some of the plots in series D, with respect to several parameters which are indicative of soil acidity, it is apparent that, compared to check plots, plots 3 (NPKS), 4 (NS) and 10 (NPS) are more acidic. Plots 6 (L) and 7 (LNPKS) are less acidic than check plots and plot 8 which receives P as $Ca(H_2PO_4)_2$, a compound having a basic reaction in the soil, is also less acidic than check plots.

With respect to values of $^{Mg}/\Sigma$ plots 3 (NPKS) and 4 (NS) are significantly lower than only one of the check plots and with respect to values of $^{K}/\Sigma$ plots 4 (NS) and 10 (NPS) are statistically lower than all three check plots, and plot 3 (NPKS) is statistically lower than one of the check plots.

(c) Soil analyses series A, B, C, D and F (plots 1-11) Ap horizon

In considering all the series together with respect

to pH, $^{Ca}/\Sigma$, $^{H}/\Sigma$, Mn and Al it is not possible to apply
statistical analysis because the plot design (see Appendix
C) is not random.

Soil analyses data for these series and plots are
presented in Tables 4, 5, 6, 7 and 8 and diagrams for pH,
$^{Ca}/\Sigma$, $^{H}/\Sigma$, Mn and Al are presented in Figures 1, 2, 3, 4
and 5. In general pH and $^{Ca}/\Sigma$ are lower and $^{H}/\Sigma$ Mn and
Al are higher in plots 3 (NPKS) and 4 (NS) than in other plots.
The reverse trends are evident for plots 6 (L), 7 (LNPKS)
and 8 (P). If the data for parameters such as pH, $^{Ca}/\Sigma$ and
$^{H}/\Sigma$ are ranked from high to low value then it is evident
that, in a given series, plots 6, 7 and 8 are less acidic
than check plots and plots 3 and 4, and in some series plot
10 (NPS), are more acidic than check plots. Furthermore,
it is also evident that plots in series D and F are generally
less acidic than their counterparts in series A, B and C.
Data presented previously, Table 2, indicated a higher "base
saturation" on series D and F than on series A, B, and C.

There are a number of other major differences
evident in the soil data for the five series. Plots 2 (M)
and 9 (MNPS) are considerably higher in %C and %N with
respect to other plots. This is obviously due to the addition
of manure having increased the organic matter content. In
some series the manured plots, particularly plot 2, have high
values of $^{K}/\Sigma$, which is also attributable to the addition
of manure which is rich in this nutrient.

Note that values for 0.05M $CaCl_2$ extractable Mn and

Table 3. Selected soil analysis data for series D (plots 1-11)

Plot	pH(H₂O)	pH(CaCl₂)	Ca/Σ †	H/Σφ	Mg/Σ	K/Σ	me/100g Ca	pH (H₂O) Second horizon ⊖
				%				
			Ap horizon					
1(CH)	6.2de*	5.6c	57.8fg	29.0b	10.2abc	2.2a	12.7c	6.4a
2(M)	6.2de	5.5c	55.7g	30.2b	10.8a	2.4a	12.9c	5.9bc
3(NPKS)	5.8g	5.1d	54.9g	33.9a	8.4e	1.6bc	11.4c	5.8c
4(NS)	6.1ef	5.4c	60.8ef	28.4bc	8.3e	1.4c	12.9c	6.2ab
5(CH)	6.4c	5.6c	64.4cd	24.1d	9.0de	1.8b	12.8c	6.5a
6(L)	6.8a	6.0a	69.6ab	17.4f	10.3abc	1.8b	14.6b	6.6a
7(LNPKS)	6.8a	6.0a	70.4a	17.7f	9.6bcd	1.7b	15.4b	6.4a
8(P)	6.6b	5.8b	66.6bc	20.8e	10.2abc	1.7b	15.4b	6.4a
9(MNPS)	6.2de	5.6c	62.0de	25.8cd	9.7bcd	1.7b	15.4b	6.4a
10(NPS)	6.0fg	5.4c	60.6ef	28.0bc	9.3cde	1.4c	15.8ab	6.4a
11(CH)	6.3cd	5.6c	63.7cde	23.2de	10.7ab	1.7b	17.2a	6.4a

* means in each column, for each parameter, followed by any common letter are not significantly
  different by Duncan's Multiple Range Test at p = 0.05.

† Σ = (Ca + Mg + Na + K + H) me/100g

φ H = Titratable acidity me/100g

⊖ Second horizon is the horizon immediately below the Ap horizon.

Table 4. Soil analyses for series A (plots 1-11)

Plot	pH (H$_2$O)	ppm Extractable		%		me/100g Exchangeable cations			
		Mn	Al	C	N	Ca	Mg	K	Na
1 (CH)	5.7	9.6	0.2	1.41	.109	12.2	2.77	0.44	0.36
2 (M)	5.9	13.0	0.2	1.89	.155	12.0	2.85	0.51	0.37
3 (NPKS)	5.3	22.2	3.4	1.64	.111	8.24	1.73	0.40	0.33
4 (NS)	5.4	16.6	0.8	1.56	.117	9.19	1.85	0.31	0.29
5 (CH)	5.9	10.0	0.0	1.54	.116	12.2	2.47	0.36	0.20
6 (L)	6.7	5.0	0.0	1.71	.109	14.0	2.68	0.34	0.21
7 (LNPKS)	6.4	6.2	0.0	1.68	.113	13.5	2.35	0.31	0.20
8 (P)	6.1	11.8	0.2	1.32	.117	12.3	2.08	0.30	0.20
9 (MNPS)	5.8	15.4	0.2	2.04	.179	12.5	2.37	0.38	0.34
10 (NPS)	5.5	17.8	1.2	1.73	.149	10.1	1.73	0.30	0.34
11 (CH)	6.0	9.5	0.0	1.40	.120	12.2	2.15	0.38	0.17

* H = Titratable acidity

† Σ = (Ca + Mg + Na + K + H)

(me/100g)		%				
$H*$	Σ †	Ca/Σ	Mg/Σ	K/Σ	Na/Σ	H/Σ
6.79	22.6	54.1	12.3	2.0	1.6	30.1
6.35	22.1	54.4	12.9	2.3	1.7	28.8
9.85	20.6	40.1	8.4	2.0	1.6	47.9
8.75	20.4	45.1	9.1	1.5	1.4	42.9
6.78	22.0	55.4	11.2	1.6	0.9	30.8
3.94	21.2	66.1	12.7	1.6	1.0	18.6
3.94	20.3	66.5	11.6	1.6	1.0	19.4
5.47	20.4	60.5	10.2	1.5	1.0	26.9
7.44	23.0	54.3	10.3	1.6	1.5	32.3
7.88	20.4	49.6	8.5	1.5	1.7	38.7
5.04	19.9	61.2	10.8	1.9	0.9	25.3

Table 5.   Soil analyses for series B (plots 1-11)

Plot	pH (H$_2$O)	ppm Extractable		%		me/100g Exchangeable cations			
		Mn	Al	C	N	Ca	Mg	K	Na
1(CH)	5.7	16.8	0.2	1.36	.116	11.5	2.77	0.42	0.20
2(M)	5.7	19.0	0.2	1.80	.140	13.4	3.50	0.48	0.16
3(NPKS)	5.3	35.0	2.4	1.53	.127	8.2	1.63	0.30	0.19
4(NS)	5.4	30.1	1.4	1.50	.126	9.84	1.93	0.28	0.19
5(CH)	5.9	15.2	0.0	1.56	.127	11.9	2.45	0.40	0.19
6(L)	6.8	13.4	0.0	1.52	.121	15.0	2.33	0.34	0.17
7(LNPKS)	6.7	15.8	0.0	1.42	.119	15.7	2.44	0.34	0.16
8(P)	6.2	10.8	0.0	1.32	.105	12.3	2.21	0.26	0.18
9(MNPS)	5.9	18.2	0.0	2.12	.167	11.6	1.91	0.36	0.24
10(NPS)	5.7	22.2	0.8	1.76	.139	11.2	1.75	0.26	0.24
11(CH)	6.0	15.4	0.0	1.36	.122	11.9	1.99	0.32	0.18

* H = Titratable acidity

† Σ = (Ca + Mg + Na + K + H)

(me/100g)		%				
H*	Σ †	$Ca_{/\Sigma}$	$Mg_{/\Sigma}$	$K_{/\Sigma}$	$Na_{/\Sigma}$	$H_{/\Sigma}$
6.57	21.5	53.6	12.9	1.9	0.9	30.6
7.44	25.0	53.7	14.0	1.9	0.7	29.8
9.63	20.0	41.1	8.2	1.5	1.0	48.3
8.32	20.6	47.9	9.4	1.4	0.9	40.5
7.44	22.4	53.2	11.0	1.8	0.9	33.2
4.38	22.2	67.5	10.5	1.5	0.8	19.7
3.72	22.4	70.2	10.9	1.4	0.7	16.6
4.59	19.6	62.9	11.3	1.4	0.9	23.5
6.57	20.7	56.1	9.2	1.8	1.2	31.8
6.34	19.8	56.6	8.9	1.3	1.2	32.1
4.82	19.2	62.0	10.4	1.7	0.9	25.1

Table 6.   Soil analysis for series C (plots 1-11)

Plot	pH (H$_2$O)	ppm Extractable		%		me/100g Exchangeable cations			
		Mn	Al	C	N	Ca	Mg	K	Na
1(CH)	5.8	14.2	0.0	1.35	.113	11.9	2.81	0.42	0.16
2(M)	5.8	14.8	0.0	1.80	.150	12.3	3.18	0.54	0.24
3(NPKS)	5.3	21.4	2.6	1.59	.129	10.9	2.16	0.40	0.33
4(NS)	5.4	18.6	1.4	1.52	.120	9.1	2.01	0.33	0.20
5(CH)	5.9	10.3	0.0	1.57	.126	10.6	2.26	0.32	0.17
6(L)	6.8	3.8	0.0	1.54	.125	14.3	2.52	0.31	0.15
7(LNPKS)	6.6	5.4	0.0	1.61	.118	16.6	2.78	0.35	0.17
8(P)	6.2	8.6	0.0	1.35	.115	15.1	3.00	0.39	0.14
9(MNPS)	6.0	12.0	0.0	2.18	.184	15.0	4.67	0.35	0.29
10(NPS)	5.8	14.5	0.8	1.71	.148	17.3	2.86	0.28	0.23
11(CH)	6.2	11.6	0.0	1.35	.120	15.7	2.68	0.43	0.17

* H = Titratable acidity

† Σ = (Ca + Mg + Na + K + H)

(me/100g)		%				
H*	Σ †	$Ca_{/\Sigma}$	$Mg_{/\Sigma}$	$K_{/\Sigma}$	$Na_{/\Sigma}$	$H_{/\Sigma}$
5.25	20.5	58.0	13.7	2.0	0.8	25.6
6.57	22.8	53.9	13.9	2.4	1.1	28.8
8.10	21.9	49.8	9.9	1.9	1.5	37.0
7.67	19.3	47.1	10.4	1.7	1.0	39.7
5.91	19.3	55.0	11.7	1.7	0.9	30.7
2.63	19.9	71.8	12.7	1.6	0.8	13.2
4.16	24.1	69.0	11.6	1.5	0.7	17.3
3.94	22.6	66.9	13.3	1.7	0.6	17.5
5.69	26.0	57.7	18.0	1.4	1.1	21.9
6.35	27.0	64.0	10.6	1.1	0.9	23.5
5.47	24.5	64.2	11.0	1.8	0.7	22.4

Table 7.   Soil analysis for series D (plots 1 - 11)

Plot	pH (H$_2$O)	ppm		%		me/100g			
		Extractable				Exchangeable cations			
		Mn	Al	C	N	Ca	Mg	K	Na
1 (CH)	6.2	10.2	0.0	1.63	.110	12.7	2.25	0.49	0.18
2 (M)	6.2	13.3	0.0	1.86	.149	12.9	2.51	0.55	0.20
3 (NPKS)	5.8	21.2	1.2	1.52	.130	11.4	1.76	0.34	0.26
4 (NS)	6.1	17.7	0.6	1.46	.122	12.9	1.75	0.30	0.25
5 (CH)	6.4	11.0	0.0	1.58	.116	12.8	1.80	0.36	0.16
6 (L)	6.8	4.4	0.0	1.56	.126	14.6	2.16	0.39	0.20
7 (LNPKS)	6.8	5.5	0.2	1.86	.120	15.4	2.11	0.36	0.19
8 (P)	6.6	8.9	0.0	1.21	.109	15.4	2.36	0.40	0.16
9 (MNPS)	6.2	13.1	0.0	2.15	.178	15.4	2.41	0.38	0.23
10 (NPS)	6.1	15.6	0.6	1.70	.149	15.8	2.42	0.35	0.23
11 (CH)	6.3	9.1	0.0	1.53	.125	17.2	2.88	0.47	0.21

* H = Titratable acidity

† Σ = (Ca + Mg + Na + K + H)

(me/100g)		%				
H*	†	Ca$_{/\Sigma}$	Mg$_{/\Sigma}$	K$_{/\Sigma}$	Na$_{/\Sigma}$	H$_{/\Sigma}$
6.38	22.0	57.8	10.2	2.2	0.8	29.0
6.97	23.1	55.7	10.8	2.4	0.9	30.3
7.03	20.8	54.9	9.4	1.6	1.2	33.9
6.04	21.2	60.8	8.2	1.4	1.2	28.4
4.80	19.9	64.3	9.0	1.8	0.8	24.1
3.64	21.0	69.6	10.3	1.8	1.0	17.3
3.83	21.9	70.4	9.6	1.7	0.9	17.7
4.79	23.3	66.6	10.2	1.7	0.7	20.8
6.42	24.9	62.0	9.6	1.7	0.9	25.8
7.76	26.1	60.6	9.2	1.4	0.9	28.0
6.28	27.1	63.7	10.7	1.7	0.8	23.2

Table 8. Soil analyses for series F (plots 1-11)

Plot	pH (H$_2$O)	ppm Extractable Mn	ppm Extractable Al	% C	% N	me/100g Exchangeable cations Ca	Mg	K	Na
1(CH)	6.1	10.4	0.2	1.50	.124	10.8	1.91	0.32	0.11
2(M)	6.3	9.2	0.0	1.83	.167	12.9	3.22	0.43	0.11
3(NPKS)	5.8	12.4	0.4	1.58	.131	12.6	1.75	0.39	0.20
4(NS)	5.9	10.9	0.2	1.54	.130	12.6	1.76	0.30	0.16
5(CH)	6.5	7.4	0.2	1.54	.137	14.3	1.78	0.33	0.12
6(L)	7.1	2.4	0.0	1.56	.132	16.6	2.06	0.32	0.14
7(LNPKS)	6.6	3.1	0.0	1.76	.125	18.1	2.18	0.36	0.14
8(P)	6.4	8.24	0.0	1.39	.120	15.7	2.30	0.32	0.15
9(MNPS)	6.1	9.2	0.0	2.30	.190	16.0	2.90	0.43	0.14
10(NPS)	5.8	12.2	0.2	1.86	.151	16.3	2.38	0.29	0.17
11(CH)	6.3	10.0	0.0	1.64	.129	18.3	3.00	0.40	0.21

* H = Titratable acidity

† Σ = (Ca + Mg + Na + K + H)

(me/100g)		%				
H*	Σ †	Ca/Σ	Mg/Σ	K/Σ	Na/Σ	H/Σ
4.12	17.3	62.6	11.1	1.9	0.6	23.9
3.28	19.9	64.7	16.2	2.2	0.6	16.5
5.69	20.6	61.1	8.5	1.9	1.0	27.6
5.47	20.3	62.1	8.7	1.5	0.8	27.0
3.94	20.5	69.9	8.7	1.6	0.6	19.3
3.06	22.2	74.9	9.3	1.4	0.6	13.8
3.50	24.3	74.6	9.0	1.5	0.6	14.4
3.50	22.0	71.5	10.5	1.5	0.7	15.9
5.69	25.2	63.6	11.5	1.7	0.6	22.6
6.35	25.5	63.9	9.3	1.2	0.7	24.9
5.92	27.8	65.8	10.8	1.5	0.8	21.3

Table 9 Correlation coefficients for soil analysis data series A, B, C, D and F

	Al	H/Σ	pH	Ca/Σ	%N	%C
Mn	0.71**	0.83**	-0.78**	-0.80**	0.11	0.00
Al	--	0.74**	-0.65**	-0.68**	-0.09	-0.05
H/Σ		--	-0.89**	-0.97**	0.02	0.03
pH			--	0.90**	-0.14	-0.06
Ca/Σ				--	-0.07	-0.08
%N					--	0.86**

** indicates significance at $p = 0.01$

Table 10. Designation and pH of the second horizon* for
series D (plots 1-11) sites I, II, III and IV

Plot	Horizon designation Site				pH (H_2O) Site			
	I	II	III	IV	I	II	III	IV
1	AB	AB	AB	AB	6.6	6.3	6.2	6.4
2	AB	AB	Ae	Ae	5.9	5.9	5.8	6.1
3	AB	AB	AB	AB	5.8	5.8	5.8	5.7
4	Ae	AB	Bt_1	AB	6.6	6.1	5.8	6.4
5	Ae	Ae	Ae	AB	6.8	6.6	6.4	6.3
6	AB	AB	AB	AB	6.7	6.6	6.5	6.7
7	AB	AB	AB	Ae	6.1	6.1	6.8	6.8
8	Ae	AB	AB	AB	6.6	6.1	6.5	6.1
9	Ae	Bt_1	Ae	AB	6.3	6.4	6.4	6.7
10	Ae	Bt_1	Bt_1	AB	6.6	6.1	6.1	6.9
11	Bt	Bt_1	Bt_1	AB	6.8	6.1	6.1	6.4

* The second horizon is the horizon immediately below the
Ap horizon.
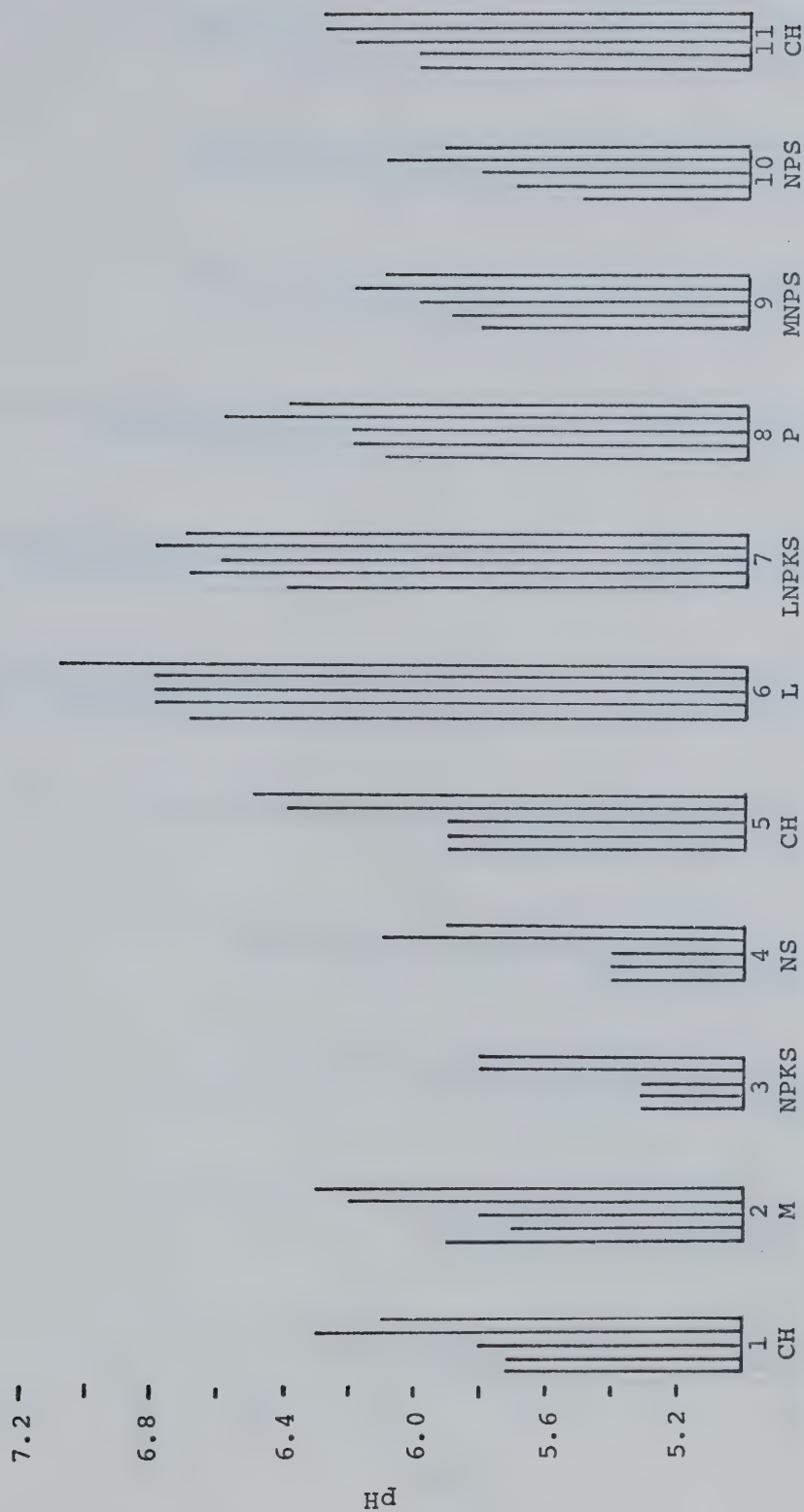
Figure 1. Soil pH Ap horizon Series A, B, C, D and F plots (1-11)
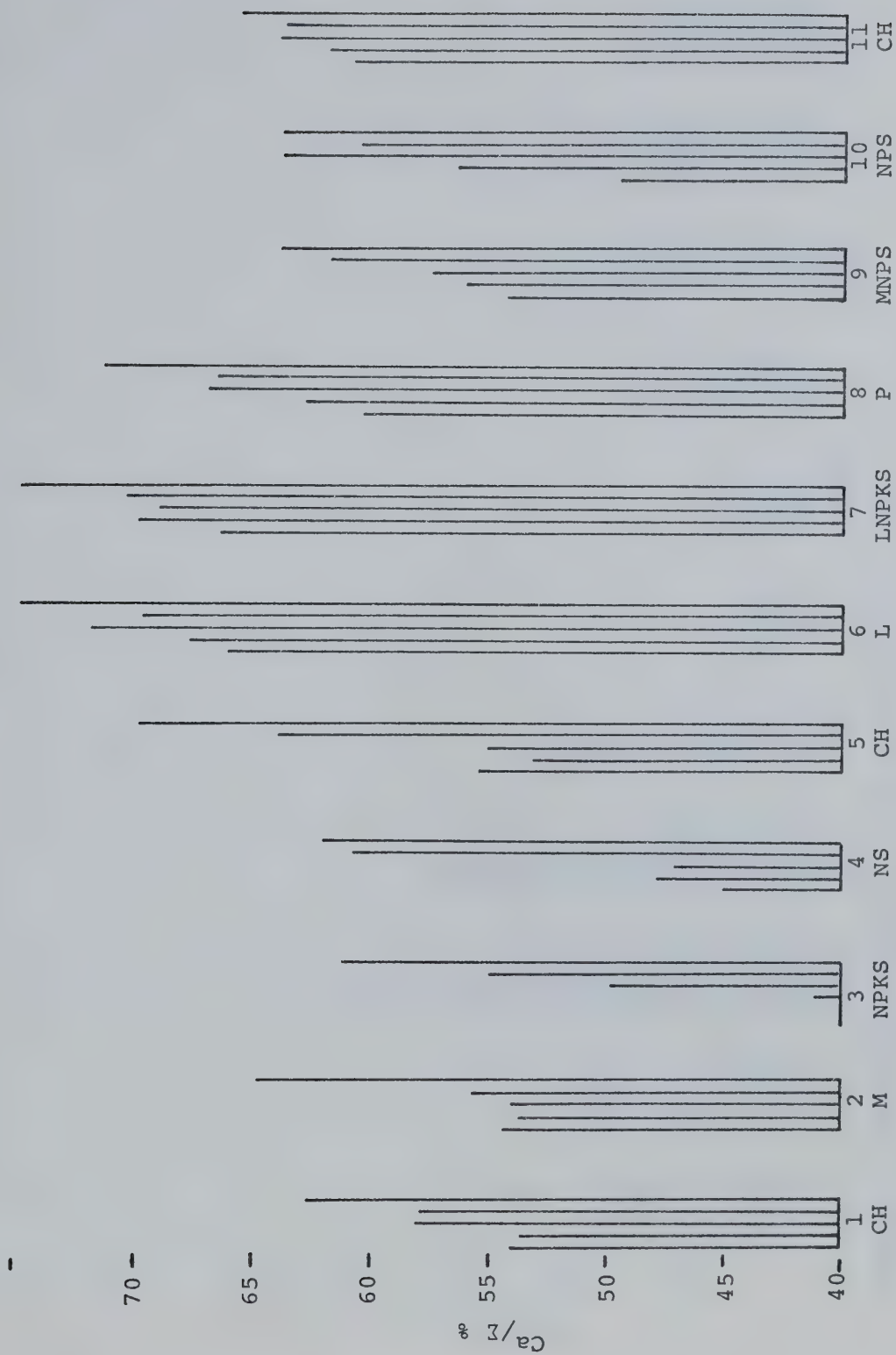
Figure 2. Soil $^{Ca}/_\Sigma$ Ap Horizon Series A, B, C, D and F plots (1-11)
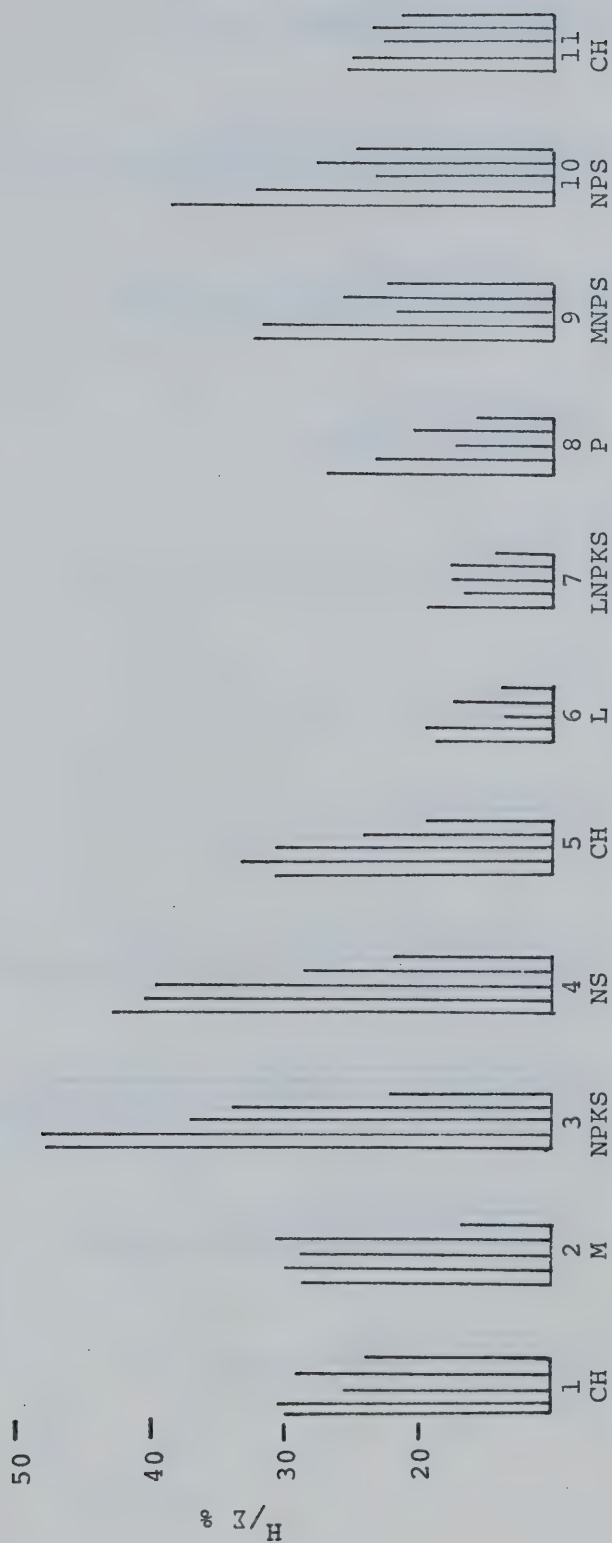
Figure 3. Soil H/Σ Series A, B, C, D and F plots (1-11)
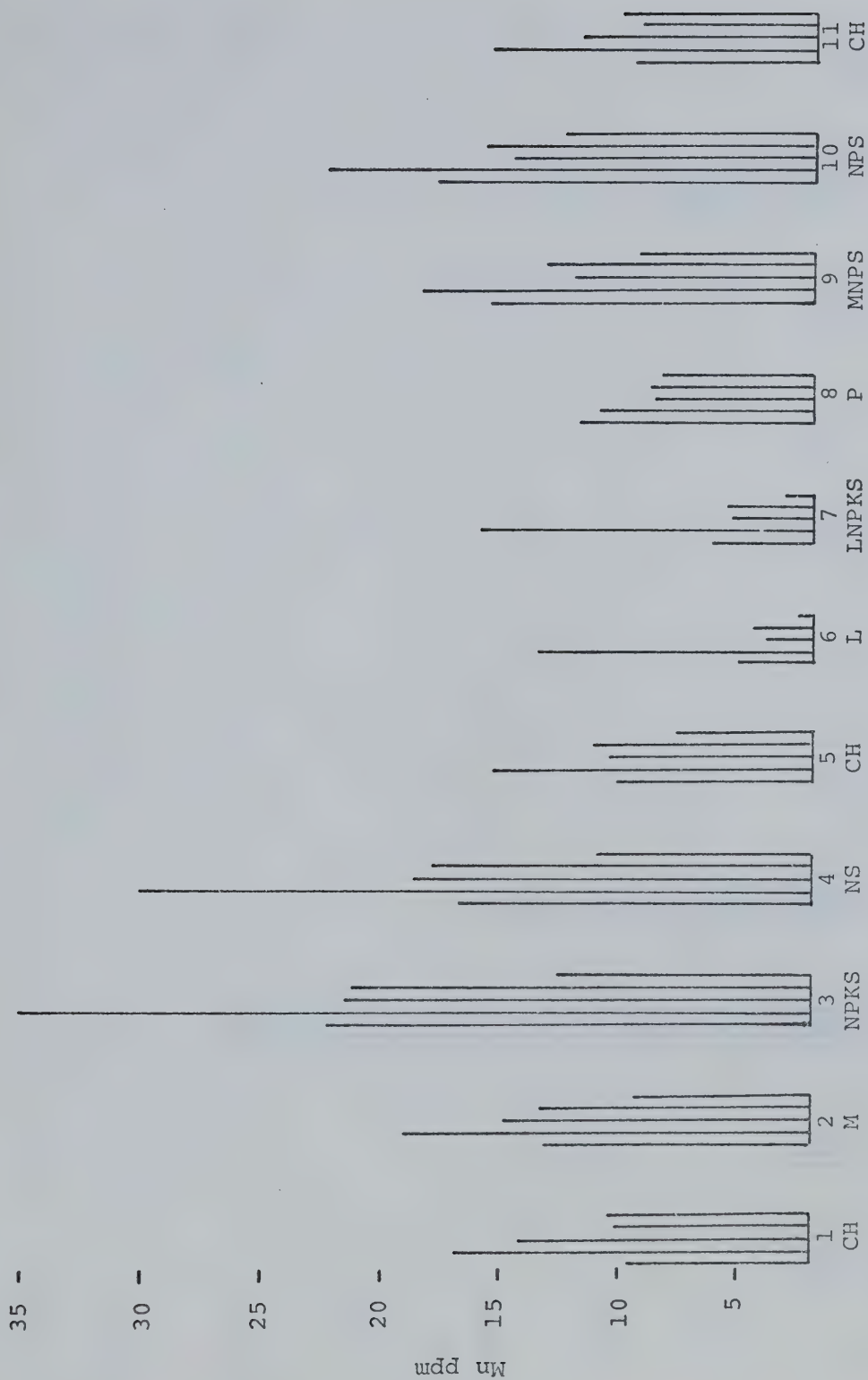
Figure 4. Soil Mn Ap horizon Series A, B, C, D and F plots (1-11)
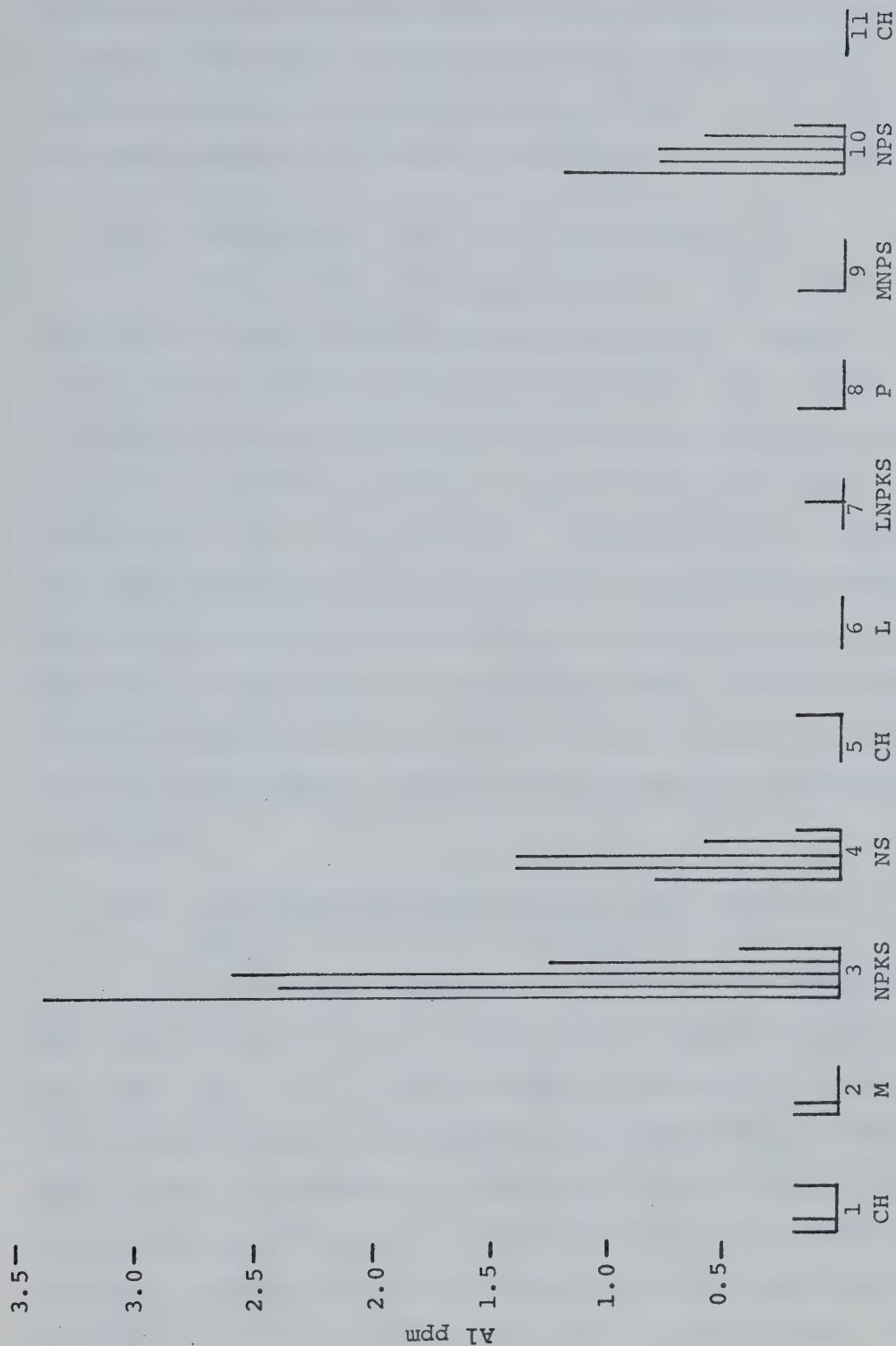
Figure 5. Soil Al Ap horizon Series A, B, C, D and F plots (1-11)

Al are not greater than 35 and 3.5 ppm respectively in any
of the plots tested. Values of Al and Mn extractable in
several solutions for plots 3 (NPKS), 4 (NS), 6 (Lime) and
10 (NPS) series C are given in Appendix B.

(d) Correlation of soil data for series A, B, C, D, and F

The soil data for series A, B, C, D and F were
examined by simple correlation to indicate the general re-
lationship between the parameters measured. The results
of some of the correlation coefficients calculated are given
in Table 9. Highly significant correlations were found
between pH, $^{Ca}/\Sigma$, $^{H}/\Sigma$, Mn and Al. The magnitude and sign
of these coefficients are as would be predicted from theory,
and serve to indicate the difficulty inherent in attributing
acid soil infertility to one variable alone. There is also
a highly significant positive correlation between soil nit-
rogen and soil carbon, which is also as would be predicted
by theory.

(e) Soil analyses series D (plots 1-11), horizon
immediately below the Ap horizon

In the virgin condition an orthic Gray Wooded soil
has the following horizon designations: L-H, (Ah or Ahe),
Ae, (AB), Bt, (Ck), C. Those horizons underlined are necessar-
ily present to meet the classification requirement. Others
may or may not be present. Under cultivation, however, sev-
eral of the top horizons may be incorporated into the Ap
horizon, so that an Ae or AB horizon where they may have
existed at shallow depth may have been so incorporated. In

general the Bt horizon of these soils has a lower pH than the Ah or Ahe horizons and the Ae and AB horizons often have a higher pH than the Ah or Ahe horizons. Mixing of these horizons by ploughing therefore may obscure differences. Furthermore, the Bt horizon, being enriched with clays, has a much higher cation exchange capacity and buffer capacity than the Ah or Ahe horizon and the Ae horizon a much lower cation exchange capacity than the Ah or Ahe horizon. Because of these general trends it was decided to separate by horizons rather than by depth. Such separation, however, requires considerable expertise and mistakes in horizon separation and designation were probably made. For example, it is difficult to decide exactly where to separate an AB from a Bt horizon, and some samples undoubtedly have material incorporated which really belongs to another horizon.

A summary of designation and pH of horizons is given in Table 10. In plots 1-8 twenty-three of the second horizons are designated AB, eight are designated Ae and one is designated Bt. In plots 9-11 inclusive three are designated AB, three are designated Ae and six are designated Bt. Values of pH of the second horizon, irrespective of designation, were treated statistically using Duncan's Multiple Range Test. The results are given in Table 3. The highest pH found was in plot 6 (lime), the lowest was in plot 3 (NPKS). This may be construed as indication of subsurface changes caused by treatment, but because of the difference in occurrence and depth of particular horizons

it is not possible to be categoric in analyses of these data. However, in plots 1, 3 and 6 the second horizon at the 4 locations was invariably designated as an AB horizon. The mean pH of these AB horizons are 6.4, 5.8 and 6.6 for plot 1 (CH) plot 3 (NPKS) and plot 6 (L) respectively, and this may be cited tentatively as evidence of subsurface changes caused by treatment.

2. Plants

(a) Separation analysis of first-year hay series D and F (plots 1-11)

Bulk samples of first-year hay from plots 1-11 in series D and F were separated into the following categories: alfalfa, clover, tame grasses, quack grass and other weeds. The results in percent based on dry-matter weight are given in Table 11. It is important to note that the forage mixture seeded since 1967 has been a mixture of alfalfa and brome grass. Forage grown on plots 2 (CH), 3 (NPKS), 4 (NS) and 10 (NPS) all have less than 30% alfalfa on both series, and plots 6 (L), 7 (LNPKS) and 8 (P, 0-45-0) all had greater than 70% alfalfa on both series. Plots 6 (L) and 7 (LNPKS) had the lowest percent clover and plots 2 (M) and 9 (MNPS) had the highest percent clover. The percentage of alfalfa in the check plots varied widely within and between series but was not less than 40%. Weeds, particularly quack grass, accounted for over 35% of forage production on plots 3, 4 and 10 of both series. Tame grasses comprised over 24% of the forage on series D plots 3 and 4

Table 11 Separation analysis of first-year hay series D and F (plots 1-11)

Series D

	1(CH)	2(M)	3(NPKS)	4(NS)	5(CH)	6(L)	7(LNPKS)	8(P)	9(MNPS)	10(NPS)	11(CH)
Alfalfa	63	22	13	15	66	86	84	70	33	24	55
Clover	10	55	20	12	5	3	3	19	40	26	6
Tame grasses	21	10	26	25	15	10	8	4	8	6	26
% Quack grass	4	12	38	44	12	--	--	4	14	38	11
Other weeds	2	1	3	4	2	1	5	3	5	6	2

Series F

	1(CH)	2(M)	3(NPKS)	4(NS)	5(CH)	6(L)	7(LNPKS)	8(P)	9(MNPS)	10(NPS)	11(CH)
Alfalfa	46	26	20	19	41	86	84	80	32	29	51
Clover	20	48	24	20	17	7	7	8	45	19	10
Tame grasses	26	6	22	18	27	3	6	3	6	13	29
% Quack grass	5	11	32	34	12	3	2	6	12	33	7
Other weeds	3	9	2	9	3	1	1	3	5	6	3

but was less abundant on series D plot 10 and series F plots 3, 4 and 10.

From these observations it may be concluded that treatments which have a basic soil reaction, namely lime and $Ca(H_2PO_4)_2$, promoted alfalfa growth and treatments containing nitrogen, NPKS, NS or NPS, did not. These latter treatments have been shown to have caused acidification and their net effect seems to have been the inhibition of alfalfa growth and perhaps promotion of competition due to grass, weeds and clover. Volunteer clover is the dominant plant on the two plots receiving manure and relatively abundant on plots 3, 4 and 10.

Apart from soil acidification caused by the NPKS, NS, and NPS treatments resulting in possible inhibition of nitrogen fixation by alfalfa, a more sensitive crop than clover, other competition effects are undoubtedly present. Plots 1 (CH) and 2 (M) on series D and F do not differ widely in soil pH, Al, Mn or $^{Ca}/\Sigma$. However, plot 2 (M) has a large clover content and low alfalfa content compared to plot 1 (CH). This may be partially due to clover seeds being present in the manure but it may also be due to direct promotion of volunteer clover growth.

(b) Observations of alfalfa root nodulation in series D and F plots 3, 5 and 7

The root systems of alfalfa plants grown on plots 3 (NPKS), 5 (CH) and 7 (LNPKS) of series D and F were examined for nodules. Nodulation was described using the

following categories and designations. Extensive +++,
good ++, poor +, no nodulation 0. The results are presented
in Table 12.

Table 12   Alfalfa root nodulation series D and F
            plots 3, 5 and 7

	Plot 3	Plot 5	Plot 7
Series D	0	+	+++
Series F	+	++	+++

The nodules of roots are easily broken in separation of soil
and root but the data do suggest that there is a close
relationship between nodulation, plant nitrogen and soil
acidity.

        The height of the plants from both the limed and
unlimed halves of series A is shown in Table 13. No
apparent increase in vigour exists between alfalfa plants
grown on the limed and unlimed halves of plots 2 (M), 5 (CH),
6 (Lime), 7 (Lime NPKS), 8 (P) and 9 (MNPS). On plots
1 (CH), 3 (NPKS), 4 (NS), 10 (NPS) and 11 (CH) plants from
the limed half are more vigorous than those on the unlimed
half. The major response to liming is evident on plots
3 (NPKS) and 4 (NS).

    (c) Chemical composition of alfalfa samples series A
         (limed), series A (unlimed), series D and F

        (1) Introduction

             Alfalfa samples taken from series A (limed
half) and series A (unlimed half) differ from samples taken
from series D and F in two important aspects. Samples from

Table 13   Average height of alfalfa plants grown on series
            A (limed) and series A (unlimed)

Plot and Treatment	Limed Half	Unlimed Half
	——————— Height cms ———————	
1 CH	38	28
2 M	33	33
3 NPKS	43	20
4 NS	28	18
5 CH	33	33
6 L	30	30
7 LNPKS	36	36
8 P, (0-45-0)	28	28
9 MNPS	23	23
10 NPS	25	23
11 CH	30	23

Table 14. Chemical composition of alfalfa grown on Series D and F (plots 1-11)

Series and Plot	ppm X10^{-1}						%		
	Mn	Fe	Al	Na	K	Ca	Mg	N	S
Series D:									
1 (CH)	4.4	2.2	2.3	12	2.1	2.3	0.24	2.8	0.16
2 (M)	4.3	2.4	1.6	11	2.3	1.8	0.22	3.3	0.24
3 (NPKS)	6.8	2.9	4.5	19	1.8	2.4	0.29	2.9	0.33
4 (NS)	5.2	2.5	3.5	22	1.7	2.5	0.28	2.9	0.32
5 (CH)	4.6	2.9	2.0	16	2.2	2.6	0.28	3.4	0.21
6 (L)	3.5	2.2	1.9	14	2.4	2.6	0.27	3.5	0.22
7 (LNPKS)	3.8	3.0	1.8	32	2.2	2.7	0.30	4.5	0.27
8 (P)	3.8	2.4	1.7	12	2.5	2.4	0.26	3.8	0.17
9 (MNPS)	4.5	2.4	2.2	27	2.2	2.2	0.29	4.2	0.28
10 (NPS)	4.9	2.8	3.4	28	2.0	2.4	0.31	3.4	0.32
11 (CH)	3.1	2.4	1.7	15	2.5	2.4	0.28	3.7	0.23

Series F:

1 (CH)	4.0	3.1	4.1	14	2.2	2.4	0.23	3.1	0.20
2 (M)	3.9	2.2	2.3	9.4	2.0	2.4	0.25	3.4	0.26
3 (NPKS)	5.7	2.4	2.7	10	1.9	2.6	0.26	2.9	0.30
4 (NS)	4.6	2.2	2.6	7.6	1.6	3.3	0.29	2.8	0.34
5 (CH)	3.6	2.1	2.7	9.4	1.9	2.4	0.23	2.9	0.21
6 (L)	3.7	2.1	1.6	16	1.9	2.4	0.23	2.7	0.25
7 (LNPKS)	3.8	2.8	1.5	12	2.3	2.4	0.25	4.4	0.30
8 (P)	3.5	2.1	1.8	16	2.0	2.1	0.22	3.0	0.15
9 (MNPS)	3.5	2.7	2.4	7.5	2.5	2.0	0.23	4.4	0.30
10 (NPS)	5.7	2.4	3.4	8.7	1.7	2.4	0.28	2.9	0.36
11 (CH)	3.6	2.1	2.5	7.1	2.2	2.5	0.27	3.0	0.25

Table 15.   Chemical composition of alfalfa grown on series A (limed) and Series A (unlimed) (plots 1-11)

Series and Plot	ppm X10^{-1}					%		
	Mn	Fe	Al	Na	K	Ca	Mg	N
Series A: (unlimed)								
1 (CH)	6.6	6.8	15	19	2.3	2.0	0.28	3.3
2 (M)	4.4	6.2	14	13	2.7	1.8	0.27	3.1
3 (NPKS)	7.3	6.7	16	50	1.7	2.5	0.36	3.2
4 (NS)	7.7	6.5	15	50	1.6	2.7	0.57	3.2
5 (CH)	5.1	6.3	12	22	2.1	2.5	0.32	3.3
6 (L)	4.2	4.7	10	19	2.0	2.3	0.34	3.1
7 (LNPKS)	4.8	5.3	10	37	1.6	2.7	0.38	3.2
8 (P)	4.7	5.5	10	41	1.8	2.5	0.38	3.1
9 (MNPS)	5.2	5.0	12	43	2.0	2.3	0.37	3.0
10 (NPS)	8.1	6.2	14	63	1.5	2.4	0.45	3.2
11 (CH)	5.3	5.0	8.8	14	2.0	2.1	0.27	3.2

Series A:
(limed)

1 (CH)	6.2	6.7	15	7.7	2.3	2.0	0.28	3.1
2 (M)	4.9	5.7	16	12	2.7	1.9	0.27	3.3
3 (NPKS)	11	7.9	19	13	2.6	2.12	0.36	2.8
4 (NS)	14	9.3	24	14	2.8	2.4	0.44	2.2
5 (CH)	5.4	5.7	15	10	2.1	2.3	0.32	3.2
6 (L)	3.8	6.6	13	25	1.9	2.6	0.36	3.0
7 (LNPKS)	5.0	5.0	10	61	1.5	2.6	0.40	3.3
8 (P)	5.5	5.0	11	27	1.9	2.5	0.38	3.1
9 (MNPS)	5.4	7.0	17	30	2.3	2.0	0.36	3.3
10 (NPS)	10	6.5	18	29	2.2	2.3	0.44	2.3
11 (CH)	4.5	4.8	9.8	6.5	2.2	2.3	0.37	3.3
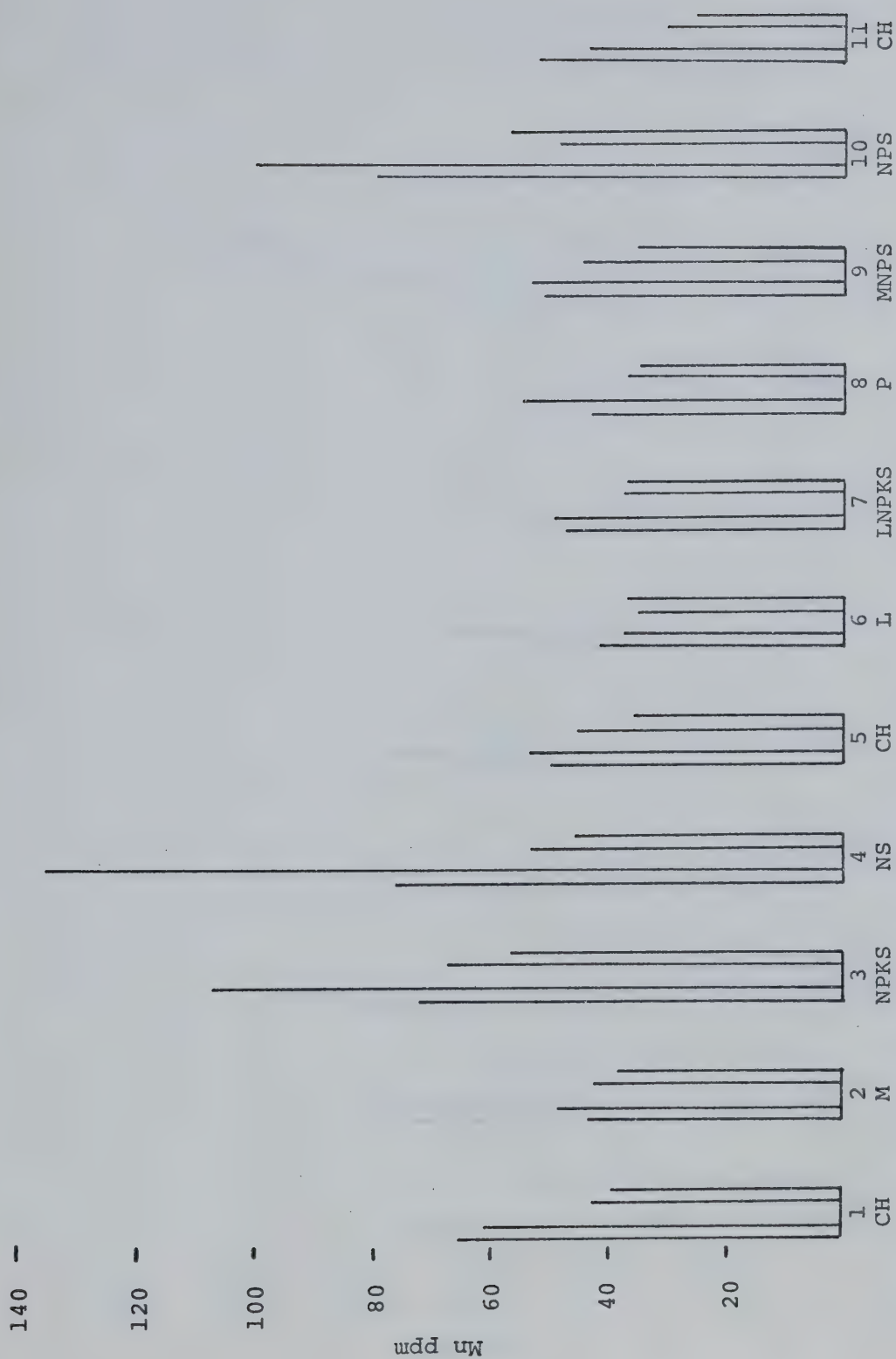
Figure 6. Plant Mn Series A (limed), A (unlimed) D and F plots (1-11)
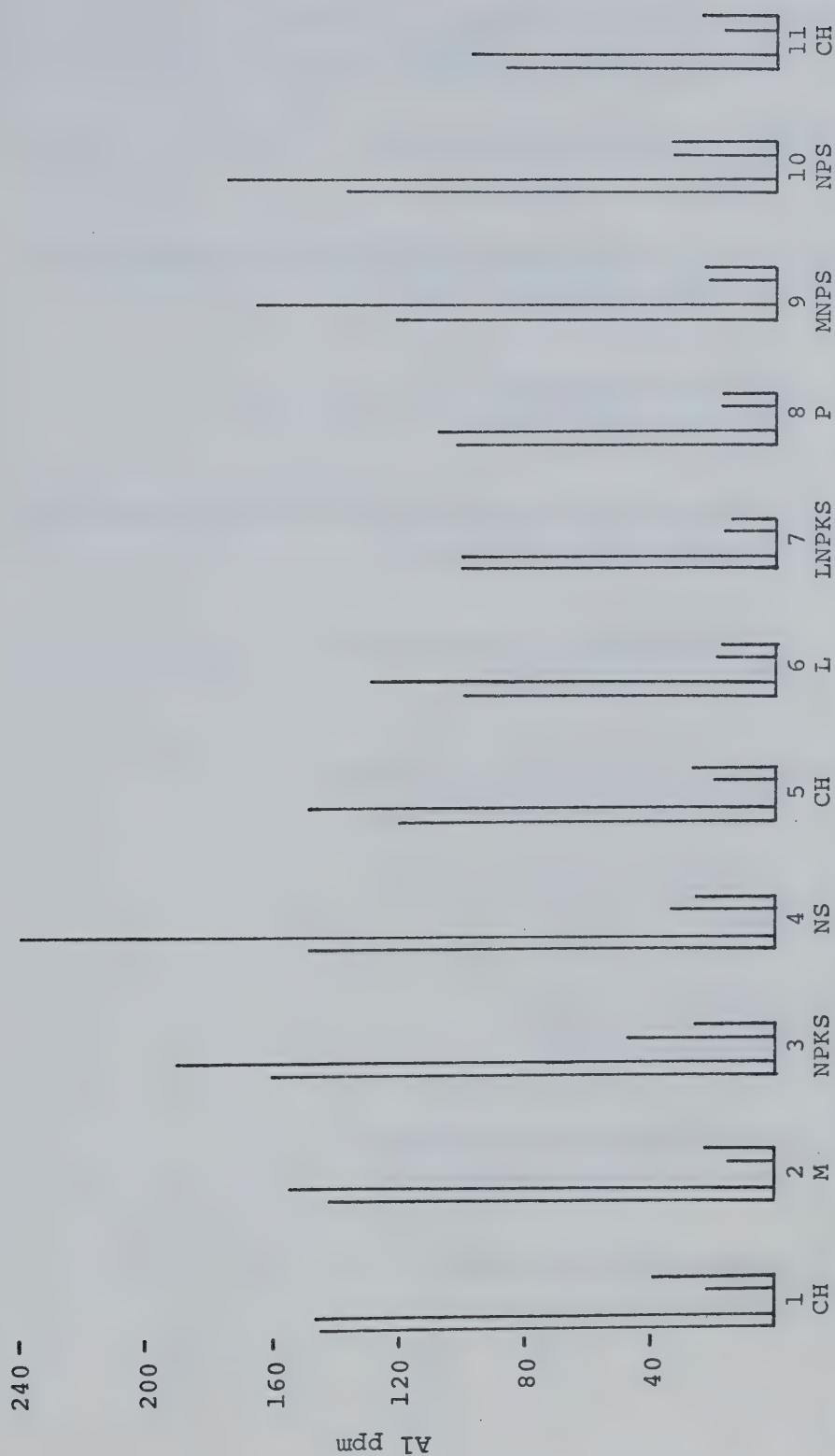
Figure 7. Plant Al Series A (limed), A (unlimed), D and F plots (1-11)
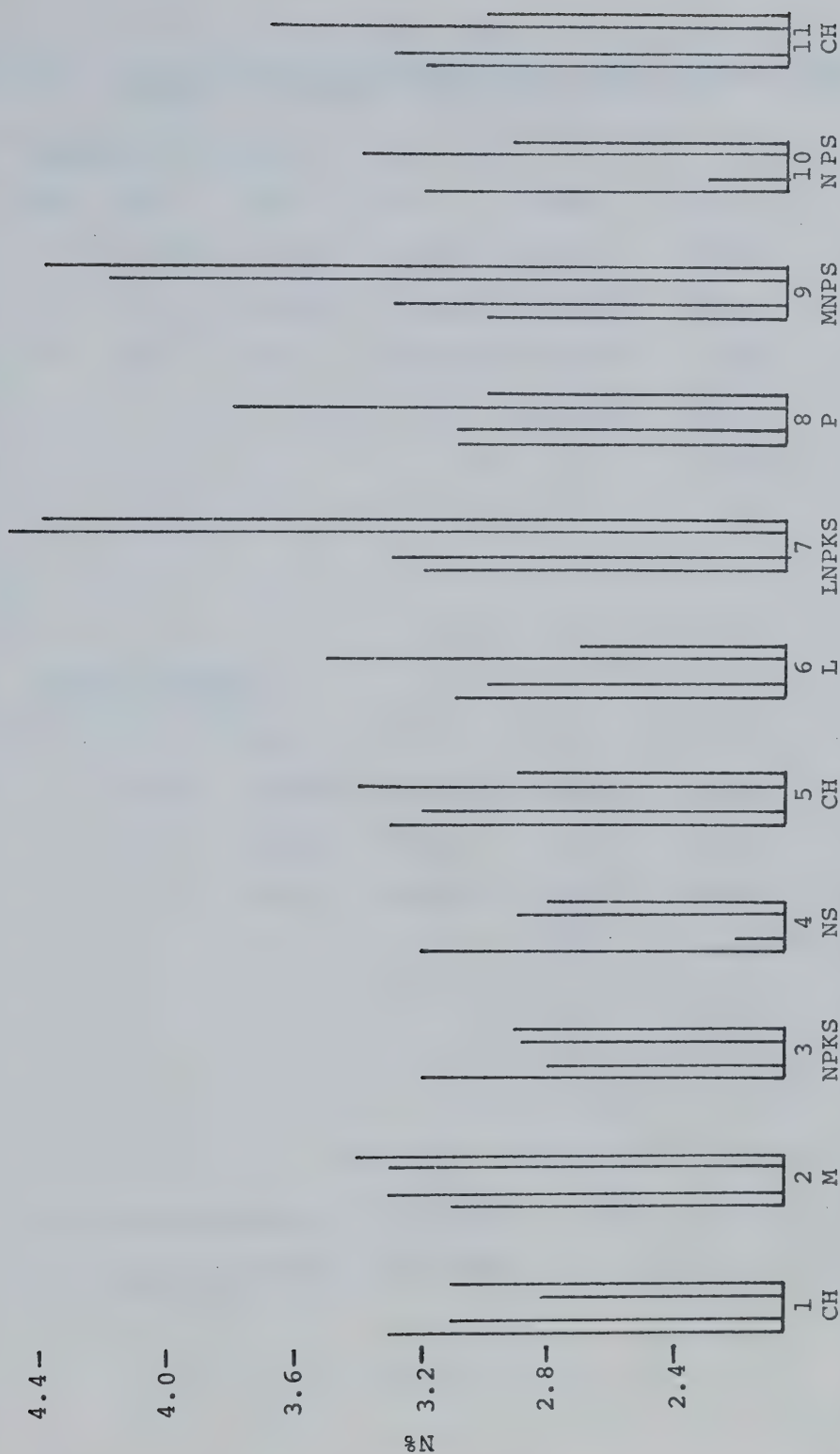
Figure 8. Plant N Series A (limed), A (unlimed), D and F plots (1-11)

Table 16   Correlation coefficients for plant analysis data
series A (unlimed) and series D and F

(a)   Series A (unlimed)

	Mn	Fe	Al	K	Ca	Mg	N
Mn	--	0.80**	0.85**	0.58	-0.05	0.56	-0.91**
Fe		--	0.92**	0.66*	-0.18	0.31	-0.73*
Al			--	0.76**	-0.33	0.26	-0.77**
K				--	-0.68*	-0.16	-0.44
Ca					--	0.62*	-0.14
Mg						--	-0.65*

(b)   Series D and F

	Fe	Al	K	Ca	Mg	N
Mn	0.29	0.68**	-0.65**	0.13	0.39	-0.39
Fe	--	0.36	0.18	0.02	0.33	0.43*
Al		--	-0.56**	0.09	0.25	-0.46*
K			--	-0.42	-0.19	0.69**
Ca				--	0.54	-0.20
Mg					--	0.19

** significant at $p = 0.01$

* significant at $p = 0.05$

series A were taken from this series when it was in the
"barley-nursing-hay" part of the rotational cycle, and the
entire plant cut 2 cm above the ground surface was sampled.
Alfalfa samples from series D and F were taken when these
series were in the "first-year-hay" part of the rotational
cycle, and the top 15 cm of plants were taken just prior
to bloom. Differences in physiological stage of growth
and the portion of the plant used in analysis may be the
main reasons why the plants in series A differ so markedly
in chemical composition from those in series D and F.
However, series A is generally a more acidic series than
either D or F and this may be partially responsible.

Simple correlation coefficients for some of the
plant analyses data are presented in Table 16. There is
highly significant correlation between Mn, Fe and Al in
the plants grown on the unlimed portion of series A, and
nitrogen in these plants is highly negatively correlated
with Mn and Al. There is a highly significant correlation
between plant Mn and plant Al in plants grown on series D
and F. Nitrogen in these plants is significantly negatively
correlated with Fe and Al but is more highly correlated
with K in the plants. The sign of the correlation coefficient
calculated between plant K and several other plant elements,
Mn, N and Al is different in plants from series A than in
those from series D and F.

(2) Aluminum and manganese content

The Al and Mn content of plants is given in

Tables 14 and 15 and Figures 6 and 7. Jones (1967) suggests
that alfalfa samples with greater than 250 ppm Mn and 400
ppm Al have excess quantities of these while those with over
100 ppm Mn and 200 ppm Al are considered high. None of the
plants from series D or F (see Table 14) approach the values
suggested as high. However, plants from series A (unlimed)
plots 3 (NPKS), 4 (NS) and 10 (NPS) have Mn concentrations
of 100 ppm or more and plants from plot 4 (NS) have an Al
concentration of 240 ppm (Table 15). However, a different
portion of the plant was taken in samples on which Jones
(1967) based his suggested values.

In most cases plants grown on the unlimed half of
plots in series A have higher Mn and Al concentration than
their unlimed counterparts. The major differences in plant
Mn and Al between the limed and unlimed halves of plots in
series A occur in plots 3 (NPKS), 4 (NS) and 10 (NPS),
which are among the most acidic. However, plant Mn and Al
concentration in the limed half of these three plots is
higher than in plants grown on the unlimed half of most of
the other plots, but these values are all below 200 ppm Al
and 100 ppm of Mn mentioned previously as being high levels
(Jones 1967). Mn and Al content of plants grown on series
D and F are lower than in series A suggesting a relative
decrease in concentration of these between first and second
year of growth. However, difference in the portion of the
plant sampled and differences in the soil of the series,
series A being in general more acidic than either D or F,

may also be important. In series D and F, as on A, plants
from plots 3 (NPKS), 4 (NS) and 10 (NPS) generally have
higher Mn and Al concentrations than plants from other plots,
and plants from plots 6 (Lime), 7 (Lime NPKS) and 8 (P,
0-45-0) have lower concentrations than plants from other
plots.

(3) Nitrogen content

The nitrogen content of plants is given in
Tables 14 and 15 and is illustrated in Figure 8. Jones
(1967) gives bench-mark values used to interpret the chem-
ical composition of alfalfa sampled in the same manner as
plants in series D and F. Using his suggested critical
values all plants with less than 4.0% N are regarded as
deficient. Using this value all plants in series D and F,
with the exception of those from plots 7 (Lime NPKS) and
9 (MNPS) are regarded as deficient. Furthermore, plants
from several plots have less than 3.0% N, a value suggested
by Bear and Wallace (1950) as being critical, these are
series D plots 1 (CH), 3 (NPKS) and 4 (NS) and series F
plots 3 (NPKS), 4 (NS), 5 (CH), 6 (Lime) and 10 (NPS). On
series A (unlimed), D and F plants from plots 3 (NPKS),
4 (NS) and 10 (NPS) generally have low nitrogen contents,
and plants from plots 7 (LNPKS) and 9 (MNPS) high nitrogen
contents compared to plants from other plots in the same
series. Plants grown on plots which receive N have, there-
fore, among the highest, plots 7 and 9, and among the
lowest, plots 3, 4 and 10, nitrogen contents. From this

observation it is clear that nitrogen application alone did not result in increased nitrogen content in plants, either because the application rate was insufficient or because nitrogen application has contributed to soil acidification resulting in reduced nitrogen utilization and inhibition of nitrogen fixation. In plot 7 (LNPKS) the lime addition is sufficient to keep the pH of the soil high enough to enable nitrogen fixation to take place and other nutrients added may promote plant growth enabling more efficient use of applied N. In plot 9 the manure may buffer the soil and enable nitrogen fixation, or the manure added may contain sufficient nitrogen and other nutrients to promote crop growth. Note that plants grown on plot 2 (M) series D and F are much lower in nitrogen than those grown on plot 9 (MNPS) on these series. This may be due to the additional nutrients added with the manure in plot 9 promoting plant growth resulting in greater uptake of nitrogen by the plant.

There are major differences evident in the nitrogen content of plants grown on the limed half of series A compared to their unlimed counterparts. Liming the east half of series A did not increase the nitrogen content of plants above 3.3% and the lowest value recorded was 3.0% in plot 9 (MNPS). The nitrogen content of plants in the unlimed half of series A ranged from 2.2 to 3.3% and the major increase due to liming one half of each of the plots in this series occurred on plots 3 (NPKS), 4 (NS) and 10 (NPS), where the nitrogen content of plants was raised to

3.2% from values of 2.8, 2.2 and 2.3% respectively. The
most plausible explanation of this is the promotion of
nitrogen fixation and the reduction of possible toxicants,
particularly Al and Mn, due to addition of lime.

(4) Potassium content

The potassium content of plants is given in
Tables 14 and 15. Jones (1967) regards alfalfa plants with
less than 1.75% K as deficient but Bear and Wallace (1950)
give a value of 2.0% K. Plants from series D plots
3 (NPKS) and 4 (NS) and from series F plots 3 (NPKS), 4 (NS),
5 (CH), 6 (Lime) and 10 (NPS) all have values less than 2.0%
and those from plot 4 (NPKS) series D and F have less than
1.75%. With the exception discussed above none of the other
values for plant analysis is either low or in excess of
values suggested by Jones (1967).

(5) Sulphur content

Sulphur content of alfalfa plants from series
D and F was determined to find out if sulphur deficiency
was a principal cause of poor alfalfa growth as it is well
established that the soil of the Breton plots is sulphur
deficient (Toogood et al. 1962). The sulphur content of
the plants (Table 14) ranged from 0.15% to 0.36% and is
generally highest in plants grown on plots receiving sulphur
application. Note that sulphur is high in plants grown on
plots 3 (NPKS), 4 (NS) and 10 (NPS), where alfalfa growth
is extremely poor, and it is also high on plot 7 (NPKS)

where alfalfa growth is vigorous. Rendig (1956) states that
sulphur content of alfalfa generally falls in the range
of 0.2 to 0.4%. The lowest sulphur content found in series
D or F was in plot 8 (P, 0-45-0) where alfalfa growth was
good. From these observations sulphur deficiency does not
seem to be the primary cause of poor alfalfa growth on the
Breton plots. However, part of the increase in alfalfa
vigour on plot 7 (NPKS) compared to plot 6 (L) may be due
to a response to added sulphur.

(d) Correlation of soil and plant data for series D
     and F and for series A (unlimed)

Plant Mn and Al are significantly correlated with
soil Mn, Al, pH, $^{Ca}/\Sigma$ and $^{H}/\Sigma$, in series D and F; see
Table 17. With respect to series A (unlimed) these plant
and soil parameters are also significantly correlated
(Table 18) with the exception of plant and soil Al. Nitrogen
in the plant is significantly correlated with soil $^{Ca}/\Sigma$ in
series D and F and is significantly correlated with soil Mn,
pH, $^{Ca}/\Sigma$, $^{H}/\Sigma$ in series A (unlimed). The correlation between
percent alfalfa and soil Mn, Al, pH, $^{H}/\Sigma$ and $^{Ca}/\Sigma$ is highly
significant in series D and F and with the exception of soil
Al the absolute value of the correlation coefficient is
greater than 0.7.

Yield of the mixed forage crop is significantly
correlated with soil Mn, pH, $^{Ca}/\Sigma$ and $^{H}/\Sigma$ and with plant
Mn at p = 0.01. Note that yield and % alfalfa are not
significantly correlated.

Table 17   Correlation of soil data, plant data, alfalfa as
            a percent of the first-year hay production, and
            yield of first-year hay on series D and F.

(a) Plant analysis data:

	Mn	Al	N
Mn	0.78**	0.72**	-0.33
Al	0.80**	0.79**	-0.33
pH	-0.68**	-0.68**	+0.30
Ca/Σ	-0.62**	-0.52**	0.53*
H/Σ	0.72**	0.60**	-0.32

(Soil Analysis Data)

(b) Soil analysis data:

	Mn	Al	pH	H/Σ	Ca/Σ
% Alfalfa	-0.80**	-0.55**	0.86**	-0.74**	0.76**
Yield	-0.54**	-0.34*	0.58**	-0.59**	0.61**

(c) Plant analysis data

	Mn	Al	K	Ca	N
% Alfalfa	-0.62**	-0.66**	0.52*	0.028	0.32
% Yield	-0.63**	-0.47*	0.51*	-0.21	0.53*

(d) Correlation between yield and % alfalfa = 0.42

              ** significant at p = 0.01

              *   significant at p = 0.05

Table 18   Correlation between soil data and plant data

Series A (unlimed)

Plant Analysis Data

		Mn	Fe	Al	K	N
	Mn	0.77**	0.60*	0.75*	0.68*	-0.60*
	Al	0.68*	0.54	0.50	0.43	-0.52
	pH	-0.80**	-0.62*	-0.75**	-0.75**	0.61*
Soil Analysis Data	Ca/Σ	-0.84**	-0.75**	-0.84**	-0.80**	0.66*
	H/Σ	0.88**	0.74**	0.83**	0.73*	-0.70*

** significant at p = 0.01

*   significant at p = 0.05

3. Greenhouse experiment

Bulk soil samples of the Ap horizon of series D plots 3 (NPKS), 5 (CH) and 7 (LNPKS) and series C plot 3 (NPKS) were taken from the Breton plots for use in a greenhouse experiment. Following air drying, sieving and mixing a sample of these soils was sent to the Alberta Soil and Feed Testing Laboratory (ASFTL) for routine analysis. The results of these analyses are given in Table 19. The following treatments were applied to soils from series C and D plot 3 (NPKS):

1. Nil

2. NPKS (50 ppm N as NH_4NO_3, 40 ppm P and 50 ppm K as KH_2PO_4, 20 ppm S as Na_2SO_4

3. NPKS (as in 2) + $Lime_1$ (to pH 6.2)

4. NPKS (as in 2) + $Lime_2$ (to pH 6.6)

5. NPKS (as in 2) + $CaCl_2$ ($CaCl_2$ applied at a rate to give a Ca addition equivalent to that added in $Lime_2$)

6. NPKS (as in 2) + Gamma radiation (12,000 rads from Co^{60} source)

7. NPKS (as in 2) + 0.05 ppm Mo as Na_2MoO_4

8. NPKS (as in 2) + nutrient solution (composition given in Appendix F)

Five hundred ml of this solution were added before seeding and a further 500 ml were added, in 50 ml increments, over the 6 week growing period.

The following treatment on series D plots 5 (CH) and 7 (LNPKS) was included: NPKS (as in 2. above).

Table 19   Analyses of soils used in greenhouse experiment

			Available nutrients			
Series and plot	Field Treatment	pH	lbs/ac			
			N	P	K	S
C3	NPKS	5.2	62	12	295	5.6
D3	NPKS	5.6	4	12	230	5.4
D5	CH	6.2	2	10	235	3.8
D7	Lime + NPKS	6.6	2	30	245	2.9

A simple randomized design was used in the green-house experiment with each treatment occurring three times. Inoculated alfalfa seeds were germinated in petri dishes and the seedlings transplanted into the greenhouse pots.   The growth period was six weeks, and following the harvest of plants all roots were checked for nodulation.   Nodules were found only in one treatment D7 + NPKS but these nodules were small and not abundant.   The addition of 50 ppm of N as NH_4NO_3 obviously inhibited nodulation.

Yield of alfalfa in the greenhouse experiment is given in Table 20.   All treatments with the exception of $CaCl_2$ increased yield of alfalfa on soils from plot 3 series C and D significantly above that of the nil treatment.

Table 20   Mean alfalfa yield, dry-matter content, in the greenhouse experiment.

Trt.	Series C plot 3		Series D plot 3	
	pH of soil after the experiment	Yield gm/pot	pH of soil after the experiment	Yield gm/pot
NPKS + rad.	5.2	2.8a*	5.5	3.1a
NPKS + nut. soln.	5.3	2.7a	5.4	2.7ab
NPKS + Lime$_1$	6.2	2.5ab	6.0	2.7ab
NPKS + Lime$_2$	6.5	2.1bc	6.5	1.9c
NPKS + Mo	5.3	1.1d	5.4	2.3bc
NPKS	5.1	1.5c	5.4	1.9c
Nil	5.4	0.2e	5.7	0.7d
NPKS + CaCl$_2$	4.8	0.1e	4.9	0.4d

* means in each column followed by the same letter are not significantly different by Duncan's Multiple Range Test at p = 0.05

The highest yields recorded, for both these soils, were on the NPKS + gamma radiation, NPKS + nutrient solution and NPKS + Lime, where the yields were invariably significantly higher than the NPKS treatments. On both soils, however, the NPKS treatment produced significantly higher yields than the nil treatment, indicating that where the plants are supplied with an adequate source of NPKS they grow well and suggesting that toxicity of Al or Mn to the plant is not the primary cause of poor alfalfa growth on these soils.

However, liming the soils to approximately pH 6 and adding NPKS significantly increased the yield above the NPKS treatment. This response to liming may be partially due to a decrease in soil Al and Mn; also the decrease in pH and yield due to the $CaCl_2$ treatment is probably due to an increase in Al and Mn toxicity. Alexander (1967) indicates that mineralization is more rapid at neutral or near neutral pH, Gerretsen and DeHoop (1957) indicate that gaseous losses of nitrogen are less and Paden and Garman (1946) show that applied nitrogen is more efficiently used as soils approach neutrality. These observations suggest that liming the soil should increase nitrogen availability in the soil but the higher rate of liming, to pH 6.5 resulted in lower yields of alfalfa on both soils, than the lower liming rate. The mean yield of alfalfa grown on series D plot 5 (CH) and series D plot 7 (LNPKS) were 2.0 and 2.9 gm/pot respectively. The pH in these soils after the experiment were 6.0 and 6.5 respectively. This indicates that the soil limed to pH 6.5 in the field had a much greater alfalfa yield in the green-house than the two soils limed to pH 6.5 in the greenhouse, though in all three cases equal rates of NPKS were added. On soils from plot 3 series D and F gamma radiation and nutrient solution addition, in combination with NPKS, gave the highest yields recorded. Bowen and Cawse (1964) indicate that 5 megarads of gamma radiation increased the concentration of K, Mg, P, C, N, S, Cu and Mn in soil solution. Major increases occurred in the concentrations of P, C, $N(NH_4^+)$

and Mn. They attribute the bulk of the increase in C, N, and most inorganic elements in solution to be from lysed microbial cells, but suggest that the increase in Mn may be due to the reduction of insoluble manganese oxides resulting in more soluble manganic species. Eno and Popenoe (1963) demonstrated that N and P were released by gamma radiation and resulted in increased plant uptake of these nutrients, but found no increase in Ca, Mg and K availability.

The ability of gamma radiation to increase the availability of many micro and macro nutrients may explain the increase in alfalfa growth on the soils treated in this manner. Similarly the treatments which received large doses of the complete nutrient solution obviously resulted in an increase in available nutrients resulting in increased crop growth. On one soil, series D plot 3, the NPKS + Mo treatment significantly increased plant yield compared to NPKS alone: however, on the other soil this treatment resulted in a decrease in yield compared to NPKS alone.

In conclusion it is evident that soils from plot 3 of two series, C and D, when supplied with NPKS in the greenhouse produced significantly greater yields of alfalfa than the nil treatment. Even greater alfalfa yields, however, were produced in response to other treatments, especially NPKS + gamma radiation, NPKS + nutrient solution and NPKS + Lime$_1$. These observations suggest nutrient availability rather than Al and Mn toxicity is primarily responsible for the poor alfalfa growth on the nil treatment.

However, the NPKS + Lime$_1$ treatment yielded more than the NPKS treatment and this response to lime may be due to reduction of Al or Mn in the soil.

E.   GENERAL CONCLUSIONS

It is evident from the soil analysis data that significant changes in the chemistry of the soil of the Breton plots have been caused by fertilizer treatments and soil amendments.   These changes are evident primarily in the Ap horizons of plots which have received fertilizers containing nitrogen and sulphur; plot 3 (NPKS), plot 4 (NS) and plot 10 (NPS), and in those plots which have received treatments having a basic soil reaction; plots 6 (Lime), 7 (Lime NPKS) and 8 (P, 0-45-0).   In the former group the soils are generally more acidic than the check plots with respect to a number of soil parameters indicative of soil acidity, namely pH, $^H/\Sigma$, $^{Ca}/\Sigma$, Mn and Al.   In plots 6, 7 and 8 the soils are generally less acidic than check plots with respect to these parameters.   The percent of the mixed stand which is comprised of alfalfa, on the series D and F where this was determined, is closely correlated with soil pH, $^{Ca}/\Sigma$, $^H/\Sigma$, Mn and Al.   Plots having a pH of 6.6 or greater had a stand consisting of at least 70% alfalfa. Those having a pH of less than 6.0 had a forage stand con-sisting of less than 30% alfalfa, and the major plant species growing on them was quack grass and other weeds. The sensitivity of alfalfa _Medicago sativa_ and the even

greater sensitivity of its symbiotic bacteria, Rhizobia
meliloti, are discussed by many authors (Munns 1965a;
Robson 1969; Nutman 1965; Ouellette and Dessureaux 1958;
Foy 1964). Munns (1965a) suggests that in moderately acid
soils (pH 5.5 - 6.0) growth limitation of alfalfa is due to
restriction of the Rhizobia and hence nodulation, but that
in strongly acid soils nodulation restriction and aluminum
toxicity were both involved in restricting the host plant.
A number of observations suggest that limitation of nitrogen
fixation is the primary cause of poor alfalfa growth on the
more acidic plots 3(NPKS) 4 (NS) and 10 (NPS). These are
as follows:

(a)   observations of nodulation of the root systems
      indicate plot 3 (NPKS) series D and F had very
      few nodules compared to either plot 5 (CH) or
      plot 7 (Lime NPKS),

(b)   the increase in nitrogen content in plants grown
      on plots 3 (NPKS), 4 (NS) and 10 (NPS) series A
      due to liming the east half of this series,

(c)   when soils from series D and C plot 3 (NPKS)
      were supplied with 50 ppm N in a greenhouse
      experiment alfalfa plants grew vigorously compared
      to the untreated soil.

There are, however, a number of important deviations which
do not support this hypothesis and suggest that in some
instances other factors may be important. These are as
follows:

(a) the NPKS + Lime$_1$ treatment in the greenhouse
experiment produced a much greater yield of alf-
alfa than the NPKS treatment alone even though
no nodules were evident in the plant roots in
either case. This response may be due to a
decrease in the activity of Mn and Al in soil
solution. Although Mn and Al in the soil and
plants were not generally high they are closely
correlated with one another and liming the east
half of series A resulted in reduction of plant
Mn and Al especially in plots 3 (NPKS), 4 (NS)
and 10 (NPS),

(b) the nitrogen content of plants grown in plots
3 (NPKS), 4 (NS) and 10 (NPS) series D and F
are not much less than those of the check plots
yet alfalfa growth was much more abundant in
the check plots. This may be due to promotion
of other species by adding fertilizer, a point
emphasized by Bear and Wallace (1950), and
also may be due to the generally higher Al and
Mn content of the plants from plots 3 (NPKS),
4 (NS) and 10 (NPS) compared to the check plots,

(c) on at least one plot, plot 6 (L) series F, low
nitrogen content of the plant cannot be attrib-
uted to inhibition of nodulation due to soil
acidity or to Al and Mn toxicity to the plant.
This plot has the highest pH, 7.1, recorded in

any plot of any of the series, and the alfalfa
grown on it has the lowest nitrogen content
recorded in series D and F. Although alfalfa
comprised a very high proportion of forage
production, 84%, the yield was much less than
in plot 7 (Lime NPKS). Plant K and S
were low in the alfalfa plants grown on series
F plot 6 (Lime) and this may partially explain
the poor vigour of the alfalfa grown on this
plot. Plant K and plant N have a correlation
coefficient of 0.69 on series D and F and
liming has been reported to reduce K uptake in
other plants (Jackson et al. 1967; Thomas and
Hipp 1968). Toogood et al. (1962) indicate
that the Breton soil is sulphur deficient.

In summary it seems evident that the poor growth of
alfalfa on plots receiving moderate applications of nitrogen
and sulphur fertilizers at Breton is largely attributable
to inhibition of nitrogen fixation due to induced acidity
caused by these compounds. Other factors such as Al and Mn
toxicity and competitional effects between species in the
mixed forage stand may be important. Manure treatments pro-
mote the growth of clovers and nitrogen and sulphur applied
without lime or manure may directly promote weed growth by
increasing soil acidity.

The project has demonstrated that the application of
small amounts of commonly available and recommended fertil-
izers over a long period increased acidity in a Gray Wooded
soil, while infrequent applications of small amounts

of lime prevented this development. The increase in acidity caused by fertilizer application resulted in a decrease in alfalfa growth in a mixed forage stand. These observations are important for a number of reasons including the following:

1. Gray Wooded soils comprise at present approximately 15% of the cultivated acreage of the province of Alberta but it is estimated that in future years they will constitute approximately 40% of the total cultivated acreage (Bentley et al. 1971).

2. Farmers on Gray Wooded soils are recommended to produce forage crops in rotation with others (Bentley et al. 1971) and alfalfa, because of its ability to fix nitrogen, high yield and protein content, is among the most attractive forage crops.

3. The use of fertilizers on Gray Wooded soils will undoubtedly increase and if not accompanied by lime application this will have dire consequences.

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APPENDIX

APPENDIX A   Soil analysis data for series D plot 1(CH)

Site	Depth cm	Horizon	pH (H$_2$O)	pH (CaCl$_2$)	CEC	Exchangeable cations me/100g Ca	Mg	Na	K	H*
I	0-19	Ap	6.3	5.6	15.0	13.2	2.37	0.13	0.53	6.27
	19-22	AB	6.6	5.7	13.6	11.5	2.26	0.25	0.51	4.81
	22-48	Bt$_1$	5.9	4.9	28.6	22.5	4.84	0.22	0.95	8.31
II	0-15	Ap	6.2	5.6	14.3	12.8	2.11	0.21	0.54	6.26
	15-19	AB	6.3	5.5	14.8	11.6	2.06	0.28	0.44	6.56
	19-75	Bt$_1$	5.8	4.9	25.8	22.6	4.84	0.22	0.63	8.53
III	0-12	Ap	6.1	5.6	15.2	12.6	2.26	0.18	0.43	6.21
	12-16	AB	6.2	5.4	16.3	12.1	2.26	0.18	0.54	7.66
	16-60	Bt$_1$	5.9	4.9	26.0	22.6	4.94	0.22	0.73	8.10
IV	0-15	Ap	6.3	5.4	14.8	12.3	2.26	0.22	0.44	6.78
	15-20	AB	6.4	5.3	21.9	18.9	3.86	0.14	0.662	6.78
	20-70	Bt$_1$	6.0	5.1	36.9	27.2	5.30	0.26	0.83	8.10

* H = Titratable acidity

APPENDIX A   Soil analysis data for series D plot 2 (M)

Site	Depth cm	Horizon	pH (H$_2$O)	pH (CaCl$_2$)	CEC	Exchangeable cations me/100g				H*
						Ca	Mg	Na	K	
I	0–16	Ap	6.1	5.6	16.6	13.6	2.83	0.20	0.63	7.13
	16–40	AB	5.9	4.9	25.7	21.6	5.45	0.31	0.95	8.10
	40–97	Bt$_1$	5.9	4.6	24.6	19.9	4.54	0.23	0.59	8.10
II	0–19	Ap	6.2	5.5	16.8	13.8	2.78	0.16	0.66	7.59
	19–43	AB	5.9	4.9	27.0	21.5	5.35	0.37	0.95	9.41
	43–79	Bt$_1$	5.7	4.6	24.2	21.6	4.73	0.28	0.62	8.75
III	0–20	Ap	6.1	5.4	15.0	12.7	2.37	0.21	0.46	6.61
	20–49	Ae	5.8	4.6	22.6	17.4	4.27	0.28	0.42	9.20
	49–99	Bt$_1$	5.9	4.8	25.2	22.6	4.42	0.31	0.63	8.31
IV	0–20	Ap	6.2	5.4	13.0	11.4	2.06	0.22	0.44	6.56
	20–25	Ae	6.1	5.5	8.7	6.81	1.49	0.13	0.27	3.94
	25–31	AB sandy	6.2	5.3	10.6	8.98	2.06	0.23	0.23	3.94
	31–96	Bt$_1$	5.8	4.7	25.4	22.0	4.89	0.31	0.59	9.41

* H = Titratable acidity

APPENDIX A   Soil analysis data for series D plot 3 (NPKS)

Site	Depth cm	Horizon	pH (H$_2$O)	pH (CaCl$_2$)	CEC	Exchangeable cations me/100g				
						Ca	Mg	Na	K	H*
I	0-18	Ap	5.7	5.2	12.3	9.42	1.54	0.23	0.31	7.11
	18-28	AB	5.8	5.0	16.2	12.5	2.62	0.28	0.39	6.56
	28-100	Bt$_1$	5.6	4.5	26.2	21.0	4.53	0.22	0.56	8.99
II	0-19	Ap	5.7	5.0	15.8	12.2	2.18	0.38	0.41	7.90
	19-36	AB	5.8	4.8	25.8	20.6	4.22	0.32	0.66	8.53
	36-94	Bt$_1$	5.6	4.7	25.2	24.0	4.48	0.22	0.51	8.97
III	0-18	Ap	5.7	5.0	14.4	11.2	1.65	0.21	0.34	6.56
	18-33	AB	5.8	4.8	23.6	18.6	3.91	0.26	0.62	8.97
	33-90	Bt$_1$	5.8	4.7	29.3	23.6	4.84	0.28	0.59	8.97
IV	0-16	Ap	5.9	5.1	15.2	12.9	1.65	0.22	0.30	6.56
	16-50	AB	5.7	4.8	22.0	18.6	2.89	0.26	0.59	8.42
	50-80	Bt$_1$	5.8	4.8	23.4	22.6	4.58	0.28	0.56	8.31

* H = Titratable acidity

APPENDIX A   Soil analysis data for series D plot 4 (NS)

Site	Depth cm	Horizon	pH (H$_2$O)	pH (CaCl$_2$)	CEC	me/100g Exchangeable cations				
						Ca	Mg	Na	K	H*
I	0-14	Ap	6.2	5.6	15.0	13.8	1.75	0.18	0.29	5.45
	14-18	Ae	6.6	5.8	19.7	17.3	3.09	0.20	0.42	3.50
	18-48	AB	6.0	5.0	24.0	20.7	4.17	0.27	0.51	6.78
	48-98	Bt$_1$	5.8	4.8	23.1	21.4	4.48	0.26	0.55	7.22
II	0-17	Ap	5.9	5.3	15.2	12.9	2.16	0.35	0.35	6.45
	17-31	AB	6.1	5.5	18.8	14.4	3.96	0.29	0.60	7.22
	31-84	Bt$_1$	5.6	4.6	25.7	23.5	4.63	0.22	0.55	9.41
III	0-15	Ap	6.1	5.5	13.4	13.2	1.44	0.31	0.30	7.00
	15-75	Bt$_1$	5.8	4.6	25.5	21.3	4.32	0.29	0.62	8.97
	75-117	Bt$_2$	6.2	5.1	26.7	25.8	4.42	0.31	0.56	6.78
IV	0-20	Ap	6.3	5.4	12.4	11.7	1.65	0.18	0.25	5.25
	20-30	AB	6.4	5.8	21.8	20.5	3.81	0.17	0.45	6.13
	30-80	Bt$_1$	5.6	4.6	24.0	23.7	4.63	0.27	0.59	9.19

* H = Titratable acidity

APPENDIX A   Soil analysis data for series D plot 5(CH)

Site	Depth cm	Horizon	pH (H$_2$O)	pH (CaCl$_2$)	CEC	Exchangeable cations me/100g				
						Ca	Mg	Na	K	H*
I	0–18	Ap	6.4	5.5	12.8	11.8	1.54	0.15	0.26	4.75
	18–21	Ae	6.8	6.1	15.9	14.5	2.88	0.26	0.38	4.81
	21–46	AB	5.6	4.5	25.9	18.9	4.17	0.24	0.57	9.19
	46–76	Bt$_1$	5.7	4.6	27.9	23.2	4.99	0.26	0.63	9.19
II	0–20	Ap	6.3	5.5	14.2	13.2	1.96	0.16	0.44	5.27
	20–30	Ae	6.6	6.0	18.7	16.8	3.29	0.28	0.50	4.81
	30–62	Bt$_1$	5.6	4.6	23.0	20.1	4.12	0.18	0.57	8.53
III	0–18	Ap	6.5	5.8	13.5	13.0	1.75	0.14	0.34	4.81
	18–24	Ae	6.4	5.5	11.7	9.40	2.04	0.18	0.64	3.50
	24–64	Bt$_1$	5.8	4.8	29.8	22.2	5.20	0.22	0.68	8.1
IV	0–16	Ap	6.6	5.8	13.6	13.3	1.96	0.17	0.40	4.38
	16–36	AB	6.3	5.5	25.2	20.8	4.42	0.16	0.77	6.78
	36–66	Bt$_1$	5.8	4.6	24.2	23.0	4.63	0.27	0.62	9.19

* H = Titratable acidity

APPENDIX A   Soil analysis data for series D plot 6(L)

Site	Depth cm	Horizon	pH (H$_2$O)	pH (CaCl$_2$)	CEC	Exchangeable cations me/100g				
						Ca	Mg	Na	K	H*
I	0-18	Ap	6.7	5.9	14.2	14.0	2.06	0.13	0.37	3.50
	18-34	AB	6.7	5.9	24.0	21.5	4.63	0.24	0.63	6.78
	34-69	Bt$_1$	5.8	4.6	24.8	20.0	4.48	0.30	0.59	8.53
II	0-16	Ap	6.6	5.8	15.0	14.0	2.26	0.26	0.45	4.29
	16-33	AB	6.6	5.8	24.1	21.0	4.73	0.29	0.72	6.35
	33-83	Bt$_1$	5.7	4.5	22.4	19.4	4.42	0.23	0.44	8.10
III	0-18	Ap	6.8	6.1	14.2	14.9	2.06	0.24	0.36	3.50
	18-33	AB	6.5	5.5	25.1	21.5	4.73	0.24	0.72	7.22
	33-73	Bt$_1$	6.1	5.0	30.2	26.4	5.19	0.27	0.59	6.35
IV	0-18	Ap	6.9	6.3	14.8	15.7	2.26	0.16	0.36	3.28
	18-44	AB	6.7	6.0	27.6	25.6	5.56	0.18	0.66	5.90
	44-98	Bt$_1$	5.7	4.7	25.0	24.2	5.24	0.34	0.62	8.53

* H = Titratable acidity

APPENDIX A   Soil analysis data for series D plot 7 (LNPKS)

Site	Depth cm	Horizon	pH (H$_2$O)	pH (CaCl$_2$)	CEC	Exchangeable cations me/100g				H*
						Ca	Mg	Na	K	
I	0-23	Ap	6.9	6.1	15.5	16.4	1.90	0.15	0.35	3.37
	23-61	AB	6.1	5.0	26.6	23.4	3.91	0.28	0.71	8.31
	61-101	Bt$_1$	6.5	5.8	25.0	26.6	4.06	0.29	0.53	6.12
II	0-18	Ap	6.7	6.0	16.0	14.4	2.21	0.29	0.40	4.29
	18-43	AB	6.1	5.2	27.5	22.3	4.94	0.29	0.65	9.41
	43-73	Bt$_1$	6.0	5.0	28.4	27.2	5.71	0.25	0.55	8.75
III	0-19	Ap	6.8	6.1	14.8	15.8	2.16	0.16	0.28	3.94
	19-29	AB	6.8	5.9	25.2	22.9	5.14	0.20	0.56	8.54
	29-59	Bt$_1$	5.9	4.8	27.3	23.2	5.50	0.23	0.55	8.10
IV	0-17	Ap	6.8	6.0	14.4	15.0	2.16	0.15	0.41	3.72
	17-22	Ae	6.8	6.1	15.0	14.1	2.42	0.16	0.41	3.65
	22-30	AB	6.6	5.9	23.0	22.9	5.92	0.24	0.63	7.22
	30-54	Bt$_1$	6.2	5.5	22.4	20.0	5.36	0.18	0.64	7.00

* H = Titratable acidity

APPENDIX A   Soil analysis data for series D plot 8(P)

Site	Depth cm	Horizon	pH (H$_2$O)	pH (CaCl$_2$)	CEC	Exchangeable cations me/100g Ca	Mg	Na	K	H*
I	0–19	Ap	6.7	5.9	14.5	15.0	2.37	0.16	0.41	4.16
	19–28	Ae	6.6	5.7	12.1	11.9	2.62	0.30	0.42	4.16
	28–34	AB	6.3	5.6	20.2	16.2	4.12	0.26	0.53	5.69
	34–64	Bt$_1$	5.6	4.6	20.4	16.3	4.22	0.21	0.53	8.31
II	0–17	Ap	6.6	5.8	15.4	16.1	2.52	0.18	0.46	4.93
	17–59	AB	6.1	5.1	24.9	21.8	5.35	0.30	0.64	7.44
	59–109	Bt	6.6	5.5	25.5	26.0	6.22	0.25	0.43	5.69
III	0–17	Ap	6.5	5.9	15.8	15.5	2.37	0.16	0.34	4.81
	17–37	AB	6.5	5.5	26.4	22.5	5.12	0.19	0.60	6.78
	37–77	Bt$_1$	5.7	4.5	31.9	25.7	5.50	0.29	0.60	9.86
IV	0–20	Ap	6.4	5.7	14.8	14.9	2.16	0.17	0.37	5.25
	20–40	AB	6.1	5.3	26.9	22.2	5.02	0.20	0.61	6.91
	40–70	Bt	6.0	4.9	22.8	22.2	4.94	0.29	0.58	5.91
	70–105	Cca	7.5	6.5	22.2	30.5	5.45	0.28	0.49	4.16

* H = Titratable acidity

APPENDIX A   Soil analysis data for series D plot 9 (MNPS)

Site	Depth cm	Horizon	pH (H$_2$O)	(CaCl$_2$)	CEC	Exchangeable cations me/100g				
						Ca	Mg	Na	K	H*
I	0-21	Ap	6.2	5.7	16.4	14.4	2.32	0.15	0.44	6.37
	21-29	Ae	6.3	5.5	12.4	9.24	2.01	0.25	0.39	5.47
	29-54	Bt$_1$	6.1	5.1	21.8	17.6	4.27	0.28	0.50	6.56
II	0-19	Ap	6.2	5.6	15.1	14.8	2.16	0.30	0.29	5.75
	19-43	Bt$_1$	6.4	5.6	27.0	24.0	5.35	0.37	0.64	7.44
	43-73	Bt$_2$	5.8	4.7	26.4	23.2	4.94	0.28	0.52	9.19
III	0-21	Ap	6.2	5.6	18.0	16.5	2.68	0.24	0.37	7.00
	21-28	Ae	6.4	5.5	12.2	10.1	2.06	0.16	0.29	4.34
	28-72	Bt$_1$	5.8	4.8	26.4	22.4	4.84	0.26	0.50	8.31
IV	0-25	Ap	6.3	5.5	16.6	16.0	2.47	0.24	0.43	6.56
	25-31	AB	6.7	6.0	21.1	21.0	4.58	0.21	0.46	5.91
	31-66	Bt$_1$	6.7	6.2	24.1	22.0	6.22	0.26	0.56	6.56

* H = Titratable acidity

APPENDIX A   Soil analysis data for series D plot 10 (NPS)

Site	Depth cm	Horizon	pH (H$_2$O)	pH (CaCl$_2$)	CEC	me/100g Exchangeable cations Ca	Mg	Na	K	H*
I	0-18	Ap	6.1	5.5	17.8	16.2	2.16	0.17	0.38	7.31
	18-25	Ae	6.6	5.6	12.2	10.5	2.01	0.27	0.31	4.16
	25-65	Bt$_1$	6.6	5.5	27.0	24.5	6.38	0.28	0.46	6.13
II	0-17	Ap	5.9	5.2	16.7	14.0	2.47	0.35	0.34	7.05
	17-43	Bt$_1$	6.1	5.2	25.3	20.8	5.04	0.28	0.56	7.44
	43-73	Bt$_2$	5.8	4.7	23.5	21.1	4.96	0.26	0.47	7.88
III	0-17	Ap	6.0	5.4	16.8	14.7	2.26	0.19	0.30	6.78
	17-42	Bt$_1$	6.1	5.1	25.7	21.8	5.22	0.18	0.59	7.66
	42-72	Bt$_2$	5.8	4.7	26.1	20.1	4.84	0.26	0.46	7.44
IV	0-17	Ap	6.2	5.5	19.2	18.4	2.78	0.22	0.37	7.88
	17-26	AB	6.9	6.4	15.5	14.3	3.28	0.14	0.34	4.16
	26-66	Bt$_1$	7.0	6.1	24.2	25.8	6.64	0.25	0.48	5.03

* H = Titratable acidity

APPENDIX A   Soil analysis data for series D plot 11(CH)

Site	Depth	Horizon	pH (H_2O)	pH $(CaCl_2)$	CEC	Exchangeable cations me/100g Ca	Mg	Na	K	H*
I	0-19	Ap	6.3	5.6	20.7	19.3	3.08	0.17	0.48	7.42
	19-57	Bt	6.8	6.0	26.1	22.7	5.87	0.23	0.61	5.69
	57-112	Cca	7.4	6.3	26.2	25.3	6.54	0.29	0.40	4.11
II	0-21	Ap	6.1	5.5	18.1	16.2	2.68	0.29	0.46	5.86
	21-45	Bt_1	6.1	5.3	26.4	22.0	5.45	0.28	0.67	7.66
	45-81	Bt_2	5.8	4.8	23.3	20.6	4.99	0.37	0.52	8.10
III	0-24	Ap	6.3	5.7	18.1	16.6	2.98	0.18	0.43	5.69
	24-64	Bt_1	6.1	5.1	24.9	20.0	4.99	0.18	0.60	7.22
	64-104	Bt_2	6.0	4.8	24.1	22.2	4.89	0.28	0.41	7.44
IV	0-19	Ap	6.4	5.7	17.7	16.8	2.78	0.18	0.48	6.13
	19-26	AB	6.4	5.8	21.6	18.4	4.42	0.16	0.54	6.56
	26-71	Bt_1	6.0	5.0	22.8	21.7	5.35	0.27	0.58	7.66

* H = Titratable acidity

APPENDIX B

Soil Al and Mn (ppm) extracted with several extractants

Series	Plot	pH	0.02M CaCl$_2$		0.05M CaCl$_2$		0.10M CaCl$_2$		1.0M KCl	
			Al	Mn	Al	Mn	Al	Mn	Al	Mn
C	3(NPKS)	5.3	1.0	10.4	2.6	21.4	5.0	24.6	11.8	28.8
C	4(NS)	5.4	0.6	9.0	1.4	18.6	4.8	19.2	8.6	23.1
C	10(NPS)	5.8	0.2	6.2	0.8	14.5	0.8	14.8	1.0	15.6
C	6(L)	6.8	0	1.0	0	3.8	0.2	4.2	0.6	3.6

Series

Plot No.
&
Treatment

1 (CH)
2 (M)
3 (NPKS)
4 (NS)
5 (CH)
6 (L)
7 (LNPKS)
8 (P)
9 (MNPS)
10 (NPS)
11 (CH)
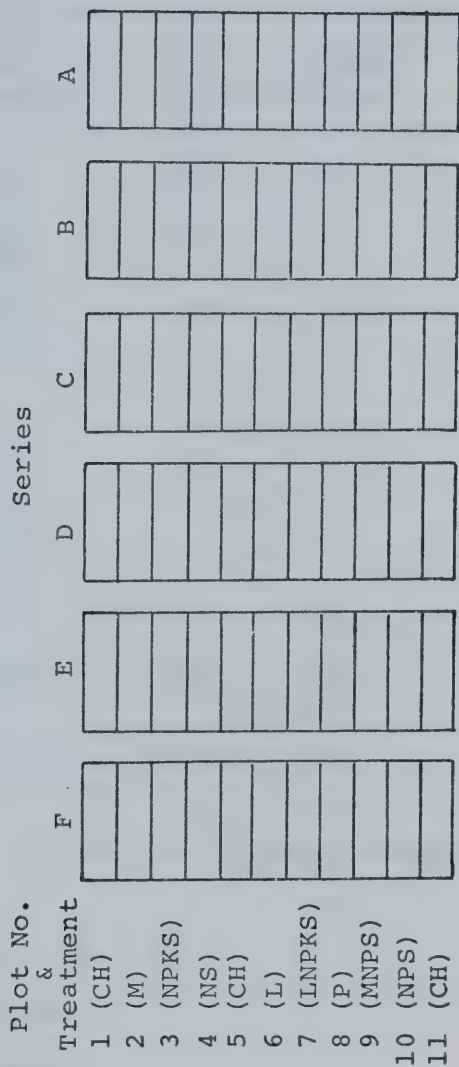
Location NE 25-47-4-W5
Scale 1" = 150'

APPENDIX C

Plan of the Breton plots.

APPENDIX C

Basic fertilizer application and treatments on plots 1-11 at Breton 1965 - present (1973)

Plot	Fertilizer	Nutrients lb/ac			
		N	P_2O_5	K_2O	S
1 (CH)	Nil	0	0	0	0
2 (M)	Manure*	200	100	200	20
3 (NPKS)	16-20-0 † 0-0-60	9.6	12	18	8.4
4 (NS)	21-0-0 † 33.5-0-0	9.6	0	0	8.4
5 (CH)	Nil	0	0	0	0
6 (Lime)	Lime φ	0	0	0	0
7 Lime NPKS	Lime φ 16-20-0 0-0-60 †	9.6	12	18	8.4
8 (P)	0-45-0 †	0	12	0	0
9 (MNPS)	Manure* 16-20-0 †	200 9.6	100 12	200 0	20 8.4
10 (NPS)	16-20-0 †	9.6	12	0	8.4
11 (CH)	Nil	0	0	0	0

* applied every 5 years

† applied every year

φ applied as needed

APPENDIX C

Lime applied at Breton on plots 6 and 7. 1930 - 1972

Year	Rate lb/ac	Series
1930	2,000	A to F
1931	1,200	A to F
1932	1,100	C and D
1933	1,100	A and D
1935	1,600	A to E
1938	2,750	F
1948	1,000	A to F

(In 1972 the east half of all plots in series A to F were limed at a rate calculated to bring the pH to 6.5.)

APPENDIX D

Percent clay (c) and sand (s), Breton Series
D, E and F Plots 1-11 *

Plot		F east	F west	E east	D west	D east
1	c	10	13	18	13	14
	s	38	38	35	39	36
2	c	13	12	15	16	16
	s	39	40	33	38	38
3	c	11	14	17	18	13
	s	38	43	40	36	35
4	c	12	14	12	14	11
	s	39	41	41	39	43
5	c	13	12	12	12	10
	s	34	36	40	40	41
6	c	13	15	16	14	12
	s	37	37	40	44	43
7	c	17	13	17	13	13
	s	36	37	38	40	41
8	c	15	16	13	13	13
	s	35	37	40	41	41
9	c	16	14	14	14	12
	s	37	37	40	35	34
10	c	15	16	15	15	16
	s	36	35	35	36	32
11	c	17	16	14	13	17
	s	33	36	36	37	33

* Unpublished data made available by Dr. J. A. Toogood

APPENDIX E

Yield of first-year hay, 1968 - 1972, Breton plots
(1-11) series A, B, C, D and F*

Series and Year

Plot and Treatment	F 1972	D 1971	C 1970 lb/ac	B 1969	A 1968
1 (CH)	3,180	1,910	966	900	730
2 (M)	3,300	3,120	3,089	1,820	1,720
3 (NPKS)	2,310	1,860	1,032	1,100	1,530
4 (NS)	2,440	1,360	947	700	1,180
5 (CH)	3,830	2,150	987	770	1,010
6 (Lime)	2,980	2,630	2,081	1,640	1,970
7 (Lime NPKS)	5,570	3,440	3,150	2,350	1,690
8 (P)	3,330	3,230	2,011	850	1,310
9 (MNPS)	3,910	2,690	2,603	1,710	1,450
10 (NPS)	2,240	2,350	1,159	1,050	1,250
11 (CH)	3,960	2,980	1,187	1,030	1,300

* Unpublished data made available by Dr. J. A. Toogood

APPENDIX F

Composition of nutrient solution used in the
greenhouse experiment

Compound	Concentration gms/litre
$CaSO_4 \cdot 2H_2O$	0.5
NaCl	0.1
$Mg\ SO_4 \cdot 7H_2O$	0.5
Fe EDTA	0.034
H_3BO_4	0.0005
$MnSO_4 \cdot H_2O$	0.0015
$Zn\ SO_4\ 7H_2O$	0.0009
$Na_2\ Mo\ O_4 \cdot 2H_2O$	0.003
$Cu\ SO_4 \cdot 5H_2O$	0.00001
$Co\ Cl_2\ 6H_2O$	0.00002